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THE CONSOLIDATED COMPARTMENT FIRE MODEL (CCFM) COMPUTER CODE APPLICATION CCFM. VENTS - PART I: PHYSICAL BASIS

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The Consolidated Compartment Fire Model (CCFM) Computer Code Application CCFM.VENTS - Part I: Physical Basis

Leonard Y. Cooper and Glenn P. Forney

ABSTRACT

A project was carried out at The National Institute of Standards and Technology (NIST) to study the feasibility of developing a new-generation, multi-room, compartment fire model computer code, called the Consolidated Compartment Fire Model (CCFM) computer code. The idea was that such a code would consolidate past progress in zone-type compartment fire modeling, and allow readily for integration of future advances with the greatest possible flexibility. Desired features of the CCFM would include: comprehensive documentation, user-friendliness, significant modularity, numerical robustness, and versatility in the sense that the code would provide a capability of analyzing a particular compartment fire problem by using any one of a range of physical-phenomena-modeling sophistication, from the most basic to the most comprehensive. The project led to the development of a prototype multi-room CCFM product called CCFM.VENTS. CCFM.VENTS involves a model formulation and code structure that allows for the required future CCFM growth flexibility. It has a relatively sophisticated and very general room-to-room forced and unforced vent flow capability. Finally, the CCFM.VENTS code uses the simplest possible, point-source-plume, smoke-filling fire physics in the rooms-of-fire-origin and a very simple heat transfer calculation there and in other spaces.

This is Part I of a four-part report which documents the above effort. Introductory remarks discuss the generic features of the CCFM and the specific features of CCFM.VENTS. The main objective of this Part I document is to present a comprehensive description of the governing equations of CCFM.VENTS and their technical basis.

The other three parts of this report are: Part II: Software Reference Guide; Part III: Catalog of Algorithms and Subroutines; and Part IV: User Reference Guide.

Some of the features of CCFM.VENTS are now in the process of being integrated into CFAST, a revised version of the FAST fire model which is being used currently in the NIST/CFR Fire Hazard Assessment Method, HAZARD.

Keywords: **building fires; compartment fires; computer models; fire models; mathematical models; vents; zone models.**

1. Background

1.1. The Consolidated Compartment Fire Model (CCFM): A New Generation Multi-Room Fire Model

A project was carried out at The National Institute of Standards and Technology (NIST) to study the feasibility of developing a new-generation, multi-room, compartment fire model computer code, called the Consolidated Compartment Fire Model (CCFM) computer code. The idea was that such a code would consolidate past progress in zone-type compartment fire modeling, and allow readily for integration of future advances with the greatest possible flexibility. The CCFM would be developed in stages and the development process would lead to a series of well-documented, user-friendly, numerically-robust, modular, and easily updated CCFM products or "applications,". These would be versatile in the sense that they would provide a capability of simulating a particular compartment fire scenario by using one of a series of available levels of physical modeling sophistication from the most basic to the most comprehensive. The final stage CCFM would provide the best possible mathematical simulation of fire-generated environments.

The project led to a prototype multi-room CCFM product called CCFM.VENTS (i.e., an application of the CCFM concept named VENTS). CCFM.VENTS involves a model formulation and code structure that allows for the required future CCFM growth flexibility.

This document, Part I: Physical Basis, is the first of a four-part report which documents CCFM.VENTS. The other three parts are: Part II: Software Reference Guide [1.1.1][1]; Part III: Catalog of Algorithms and Subroutines [1.1.2]; and Part IV: User Reference Guide [1.1.3].

CCFM.VENTS adopts and consolidates many previously established zone-type fire modeling ideas. As the discussion proceeds, this report will place the resulting features of the model into the perspective of the relevant reference sources.

1.2. Generic Features of the CCFM

Although the CCFM would be developed in stages, each stage would have certain common generic features. These are identified below.

1.2.1. The Feature of Consolidation of Past/Future Advances in Compartment Fire Modeling

The feature of consolidation means that during the CCFM development process full advantage would be taken of the significant number of proven advances of fire modeling research. While improvements and/or generalizations of

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[1]Numbers in brackets always refer to the list of references at the end of this report.

available products may be required, there should be no unnecessary duplication of fundamentally sound and proven technology.

1.2.2. The Feature of Being Well-Documented

Quality documentation, which would be critical to user-friendliness of CCFM products, must provide: details of the mathematical algorithms/submodels and associated modular subroutines for the various physical phenomena simulated; details of the numerics module(s) used to solve the governing set of the model equations; information on the structure of the overall code and the details of any utility software subroutines used to manage code simulations; and a well-written user guide which complements easy-to-use input and output software.

1.2.3. The Feature of Modularity: Code Can Receive Advanced/Improved Submodels, Solver(s), and Input/Output Software

The feature of modularity would be critical to insuring the required orderly and efficient future growth of and improvement to existing stages of CCFM products. The use of well-defined modular elements in the CCFM would also be critical for a successful team development effort. Indeed, by constructing CCFM products with modular components having well-defined inputs and outputs, a development-team effort that even involves significant inter-institution participation would be possible.

1.2.4. The Feature of User-Friendliness

User-friendliness refers to the ability of people with a reasonably wide range of technical background, other than the members of the CCFM development team, to have ready access to CCFM products. Access here refers to the ability of a serious user to: run any particular CCFM code application; modify the code as required; and extract and use modular portions of the code for the user's own particular needs. User-friendliness requires easy-to-use software which can be run on generally accessible computer hardware and which is supported by quality documentation.

1.2.5. The Feature of Flexibility - From Basic to "Reference" Modeling

Successively developed CCFM "applications" would lead to a capability for simulating a particular fire scenario with more or fewer fire-generated phenomena and with different levels and preferences of modeling sophistication. Such a range of capability would result in different kinds of user-flexibility. For example, a simulation which accounts for the complete array of available phenomena and which is treated at the highest possible level of modeling sophistication would be relatively costly, perhaps unnecessarily so, in terms of required user and computer resources. If a user does not require the maximum detail and sophistication, or is not prepared to pay the costs, then simpler or more basic CCFM simulations would be available.

1.2.6. The Feature of Inter-Institution/International Participation and Co-operation in the Development of the CCFM

There would be clear benefits to significant inter-institution and international co-operation in the development of the CCFM. These would include; the pooling of resources, the avoidance of unnecessary duplication of effort, and the generation of consensus CCFM products which would maximize appropriate proliferation and use. It is envisaged that such co-operation would be implemented by a variety of mechanisms which are now being identified.

1.3. Strategy for Achieving a Final Stage of CCFM Development

The strategy for developing the CCFM to its final stage includes the following components:

- Develop the CCFM in stages.
- Each CCFM stage would culminate in a progressively more sophisticated, well-documented, multi-room fire model computer code.
- Staged products would involve progressive consolidation of existing and developing fire modeling technology. As required, appropriate further development and improvement of this technology would be carried out.
- Development of a prototype/first stage CCFM product: CCFM.VENTS (i.e., the Consolidated Compartment Fire Model application designated as VENTS).
- Development of a second stage CCFM product (possible name CCFM.BUILDING) with significant advances over CCFM.VENTS in modeling of combustion, flow dynamics, and heat transfer; not yet of "Reference quality."
- Anticipate final, "Reference" level of sophistication in CCFM by third-to-fourth stage.

1.4. CCFM.VENTS: The Prototype/First Stage Application of the CCFM Concept

In terms of the above strategy, this documentation and the associated computer software for CCFM.VENTS completes the prototype/first stage of CCFM development.

The basic features of CCFM.VENTS include:

- multiple rooms/vents,
- concentrations of O_2 and other products of combustion,

- high or low cross-vent pressure difference,
- forced ventilation via simple fan-duct systems - user can specify flow rate or fan/duct characteristics,
- multiple, specified, time-dependent fires,
- simplest plume/heat transfer,
- stack effect,
- wind loading,
- robust solver,
- menu-driven user-friendly input,
- operation on computers that support FORTRAN 77, e.g., IBM-compatible and Apple Mac II personal computers,
- complete modularity of all physical-phenomena algorithms and associated subroutines,
- complete descriptions of all physical submodel algorithms including a catalog of all algorithms and associated subroutines,
- complete description of the structure of the code and of all associated computer software,
- user guide.

CCFM.VENTS uses a generic CCFM equation set that would be applicable for all stages of the CCFM development process. This equation set will be presented in Section 2.

A concise but complete description of the physical basis of all of the physical modeling features included in CCFM.VENTS is presented in Section 3. The material in this section constitutes the basis of the complete CCFM.VENTS-specific equation set.

Section 4 describes the method of specifying a problem for a particular CCFM.VENTS simulation. As will be seen, the varied means of specifying a problem within the context of the CCFM.VENTS inputs lead to a capability for the simulation of the phenomena of wind loading and stack effect.

This Part I presentation concludes with Section 6, which provides a summary and overview of Parts II-IV of this report.

2. The Generic CCFM Equation Set

2.1. Model Assumptions and Some Definitions

The CCFM uses a two-layer zone-type description of the fire-generated environment for all rooms of a facility. This means that the environment in each room is assumed to be comprised of one or two relatively-quiescent stratified zones which together fill essentially all of the room's fixed volume. These zones, depicted in Figure 2.1, include an elevated temperature buoyant upper layer and a relatively cool lower layer.

It is of interest to note that there are a wide range of previously developed compartment fire models which use a two-layer zone-type description of the fire environment. These include: CIT [2.1.1], Harvard V [2.1.2], RFIRES [2.1.3], ASET [2.1.4], Harvard VI [2.1.5], BRI [2.1.6], FAST [2.1.7], NBS/Harvard VI [2.1.8], DSLAYV [2.1.9], FIRST [2.1.10], CIFI [2.1.11], and MRFC [2.1.12]. While extensive, the latter list is not intended to be exhaustive.

Both layers of a room are assumed to be spatially uniform in temperature, density, and composition. During the course of a simulated fire scenario, conservation of mass and chemical species are imposed on all layers of all rooms of a modeled facility. By imposing conservation laws and specifying an equation of state for the layers, assumed here to be consistent with a perfect gas model for air, one is led to a generic set of model equations for the instantaneous layer properties in an arbitrary room. The CCFM generic set is derived in Appendix A and presented in Section 2.3. Except for variations in nomenclature, choices of solution variables, and questions related to treatment of pressure-work terms in the energy equation, there must be a fundamental equivalence between the generic layer-equation sets of different zone-models.

The properties of the layers change as a function of time by virtue of mass, energy, and species transfers from relatively small-volume plumes, jets, near-boundary flows, combustion zones, and other isolated or distributed sources. The volumes of all of these small-volume zones are assumed to be negligible. The number and types of phenomena occurring in these zones are critical to the overall model. Indeed, the number of physical and chemical phenomena taken into account, and the detail and sophistication with which such phenomena are modeled actually distinguish one overall zone fire model from another or, in the present case, one application of the CCFM generic equation set from another. The model equations for all of the source and transfer zones are designated as the submodels of the overall model. They must of course all be internally consistent with conservation laws.

Without specifying the number or details of the submodels of a particular version or application of the CCFM, the following definitions and designations are useful generally for deriving and implementing the generic CCFM equation set for a particular CCFM application:

$\dot{M}_{U,i}$ [$\dot{M}_{L,i}$] and $\dot{P}_{k,U,i}$ [$\dot{P}_{k,L,i}$] are the net rates of mass and product of combustion k flowing to the upper [lower] layer of room i, respectively.

Also, $\dot{Q}_{U,i}$ [$\dot{Q}_{L,i}$] is the net rate of enthalpy plus heat transfer plus energy release flowing to the upper [lower] layer of room i.

Note that all of the above net flow rates represent the sum of transfers to the layers from all above-mentioned plumes, jets, near-boundary flows, combustion zones, and other isolated or distributed sources considered and taken into account in any particular CCFM application.

2.2. Pressure in the Generic Layer Equations

The generic CCFM equations will take into account pressure-work terms in the energy equation. In this regard, this section will clarify the use of approximate representations of the pressure variable.

Define the dimensionless quantity

$$\delta = \rho g(y - \hat{y})/p(\hat{y}) \tag{2.2.1}$$

where y is an arbitrary elevation within a room of interest above a datum elevation, $\hat{y}$ is an arbitrary fixed value of y within the room, ρ is the density of the layer at $\hat{y}$, g is the acceleration of gravity, and p(y) is absolute pressure. In fire scenarios it is always true that

$$|\delta| \ll 1 \tag{2.2.2}$$

The two-layer modeling assumption and Eq. (2.2.2) along with the momentum equation, i.e., hydrostatics, and the perfect gas law lead to

$$p(y) = p(\hat{y})[1 + O(\delta)] \approx p(\hat{y}) \tag{2.2.3}$$

Note that although pressure differences within a room are negligible the pressure differences between one room and another may not be negligible.

The Eq. (2.2.3) approximation, adopted implicitly in all two-layer zone models, is also adopted here. In every room i, $\hat{y}$ is taken to be the elevation of the floor, $y_{FLOOR,i}$ and $p(\hat{y})$ is designated as $p_{FLOOR,i}$. Thus,

$$p_{FLOOR,i} \equiv p(\hat{y} = y_{FLOOR,i}) \text{ for room i} \tag{2.2.4}$$

Eqs. (2.2.3) and (2.2.4) are used to estimate pressure-work terms in the energy equation to a consistent level of accuracy when such terms are non-negligible.

As will be discussed in Section 3.3, calculation of p(y) to determine flow through vents due to cross-vent pressure differences will usually require accurate estimates of the $O(\delta)$ term in Eq. (2.2.3). Therefore, when calculating vent flows the approximation $p(y) \approx p(\hat{y})$ of Eq. (2.2.3), used to describe thermodynamic state variables, will not be applicable.

2.3. Generic Equation Set for An Overall Facility

2.3.1. The Generic Equation Set for An Arbitrary Room

Consider room i of a simulated facility. Define V_i as the fixed volume of the room and $V_{U,i}$ as the instantaneous volume of its upper layer, i.e., $V_i - V_{U,i}$ is the volume of the lower layer. Also, consistent with the definitions in Section 2.1, $M_{U,i}$, $M_{L,i}$ and $P_{k,U,i}$, $P_{k,L,i}$ are defined as the total instantaneous mass and amount-of-product k in the upper and lower layers, respectively.

Typical fire scenarios involve $p_{FLOOR,i}$ values which vary relatively little from a datum absolute pressure, p_{DATUM}. For example, if p_{DATUM} in a problem is taken as the local atmospheric pressure at ground elevation, of the order of 10^5 pascals, then typical variations of the $p_{FLOOR,i}$'s from p_{DATUM} will only be of the order of 10^2 pascals or less. For this reason, use of the transformed pressure variable,

$$\delta p_{FLOOR,i} = p_{FLOOR,i} - p_{DATUM} \qquad (2.3.1)$$

will lead typically to a higher level of accuracy in the computation of $p_{FLOOR,i}$. The perturbation-pressure, $\delta p_{FLOOR,i}$, is adopted as a solution variable in place of the pressure variable, $p_{FLOOR,i}$. [Note that the δ of Eq. (2.3.1) is part of the single symbol δp, and should not be confused with the δ of Eqs. (2.2.1)-(2.2.3).]

In the Appendix, the generic CCFM equation set for an arbitrary room i has been derived from application of the laws of conservation of mass, energy and species. As mentioned, pressure-work terms are taken account of in the energy equation. The equations are presented in terms of the solution variables $M_{U,i}$, $M_{L,i}$, $P_{k,U,i}$, $P_{k,L,i}$, $V_{U,i}$, and $\delta p_{FLOOR,i}$.

For rooms i of a facility with horizontal cross-sectional areas, A_i, which are uniform with elevation, (e.g., for right cylindrical rooms), the solution variable $V_{U,i}$ can be replaced by the alternate solution variable $y_{LAYER,i}$, the elevation of the interface separating the upper and lower layers.

The equations from the Appendix are reproduced below.

Mass in Upper and Lower Layers:

$$dM_{U,i}/dt = \dot{M}_{U,i} \tag{2.3.2}$$

$$dM_{L,i}/dt = \dot{M}_{L,i} \tag{2.3.3}$$

where, consistent with the definitions in Section 2.1, the terms $\dot{M}_{U,i}$ and $\dot{M}_{L,i}$ on the right-hand side of Eqs. (2.3.2) and (2.3.3) each represent the sum of individual mass flow rate contributions to the layers from all plumes, jets, sources, etc. The terms $\dot{P}_{k,U,i}$, $\dot{P}_{k,L,i}$, and $\dot{Q}_{U,i}$, $\dot{Q}_{L,i}$, to be introduced below, will represent analogous product and enthalpy flow rate contributions, respectively.

Volume of Upper Layer or Elevation of the Interface (For Rooms With Vertical Walls):

$$dV_{U,i}/dt =$$

$$\{(\gamma-1)/[\gamma(\delta p_{FLOOR,i} + p_{DATUM})]\}[(1 - V_{U,i}/V_i)\dot{Q}_{U,i} - (V_{U,i}/V_i)\dot{Q}_{L,i}] \tag{2.3.4}$$

where

$$\gamma = C_p/C_v = 1 + R/C_v \tag{2.3.5}$$

and where C_p and C_v are the specific heats at constant pressure and volume, respectively, R is the gas constant. All of these properties are approximateed by those of air.

For rooms with vertical walls, Eq. (2.3.4) can be replaced by

$$dy_{LAYER,i}/dt = [(\gamma-1)/(\gamma p_{FLOOR,i} V_i)][(y_{CEILING,i} - y_{LAYER,i})\dot{Q}_{L,i} - (y_{LAYER,i} - y_{FLOOR,i})\dot{Q}_{U,i}] \tag{2.3.4'}$$

where $y_{CEILING,i}$ and $y_{FLOOR,i}$ are the fixed elevations of the ceiling and floor of room i, respectively.

Perturbation Pressure at the Floor:

$$d\delta p_{FLOOR,i}/dt = [(\gamma-1)/V_i](\dot{Q}_{U,i} + \dot{Q}_{L,i}) \qquad (2.3.6)$$

Amount of Product k in Upper and Lower Layers:

$$dP_{k,U,i}/dt = \dot{P}_{k,U,i} \qquad (2.3.7)$$

$$dP_{k,L,i}/dt = \dot{P}_{k,L,i} \qquad (2.3.8)$$

Equation of State:

$$\delta p_{FLOOR,i} + p_{DATUM} = \rho_{U,i}T_{U,i}R = \rho_{L,i}T_{L,i}R \qquad (2.3.9)$$

Layer Densities, Temperatures, and Concentrations of Products:

$\rho_{U,i}$ and $\rho_{L,i}$, the densities of the upper and lower layer, respectively, are computed according to their definitions from the solution variables $M_{U,i}$, $M_{L,i}$, and $V_{U,i}$.

$$\rho_{U,i} = M_{U,i}/V_{U,i} \qquad (2.3.10)$$

$$\rho_{L,i} = M_{L,i}/(V_i - V_{U,i}) \qquad (2.3.11)$$

where

$$V_i = A_i(y_{CEILING,i} - y_{FLOOR,i}) \qquad (2.3.12)$$

$$V_{U,i} = A_i(y_{CEILING,i} - y_{LAYER,i}) \qquad (2.3.13)$$

With the above values of the densities, the absolute temperatures of the upper and lower layer, $T_{U,i}$ and $T_{L,i}$, respectively, are then computed from the solution variable $\delta p_{FLOOR,i}$ using Eq. (2.3.9).

$$T_{U,i} = (\delta p_{FLOOR,i} + p_{DATUM})/(\rho_{U,i} R) \quad (2.3.14)$$

$$T_{L,i} = (\delta p_{FLOOR,i} + p_{DATUM})/(\rho_{L,i} R) \quad (2.3.15)$$

Finally, $c_{k,U,i}$, $c_{k,L,i}$, the concentrations of product of combustion k in the upper and lower layer, respectively are computed from the solution variables according to their definitions.

$$c_{k,U,i} = P_{k,U,i}/M_{U,i} \quad (2.3.16)$$

$$c_{k,L,i} = P_{k,L,i}/M_{L,i} \quad (2.3.17)$$

The final set of generic equations for the solution variables is Eqs. (2.3.2)-(2.3.8). Evaluation of the terms $\dot{M}_{U,i}$, $\dot{M}_{L,i}$, $\dot{P}_{k,U,i}$, $\dot{P}_{k,L,i}$, $\dot{Q}_{U,i}$, and $\dot{Q}_{L,i}$ which appear on the right sides of these equations will be discussed in the next section. The derived variables, $\rho_{U,i}$, $\rho_{L,i}$, $T_{U,i}$, $T_{L,i}$, $c_{k,U,i}$, and $c_{k,L,i}$, are computed from the solution variables by using Eqs. (2.3.10)-(2.3.17).

2.3.2. Forming the Equation Set for the Facility

To use the CCFM to simulate a fire scenario it is generally necessary to solve simultaneously the complete equation set for all solution variables, described in Section 2.3.1, for each room, i, of the facility. In such an equation set, the equations for the solution variables $M_{U,i}$, $M_{L,i}$, $V_{U,i}$ (or $y_{LAYER,i}$, for rooms i with vertical walls), $\delta p_{FLOOR,i}$ will always be coupled (i.e., the variables appear implicitly or explicitly in equations other than their own), while the equations for the $P_{k,U,i}$, and $P_{k,L,i}$, k = 1 to N_{PROD} may be uncoupled (i.e., the variables do not appear implicitly or explicitly in any equation other than their own). Thus, if the number of rooms in a simulated facility is N_{ROOM}, the number of coupled solution equations in the overall differential equation set will be between $4 \cdot N_{ROOM}$ and $(4 + N_{PROD}) \cdot N_{ROOM}$. (In the present context, O_2 would be considered as one of the N_{PROD} products of combustion.) As will be seen, in the present CCFM application code, CCFM.VENTS, the differential equations for the $P_{k,U,i}$, and $P_{k,L,i}$ are always uncoupled and the number of coupled differential equations is $4 \cdot N_{ROOM}$.

For CCFM.VENTS, the generic equations are implemented with the assumption that all rooms of a modeled facility are right cylinders, i.e., Eqs. (2.3.12) and (2.3.13), with elevation-independent A_i, are applicable and Eq. (2.3.4') is used instead of Eq. (2.3.4).

The generic equation set for the fire environment describes explicitly the state of the two gas/smoke layers in each room of the facility. Heat and mass transfer exchanges between the surfaces of the solid partition elements of the rooms and the gas layers are included implicitly in the terms $\dot{M}_{U,i}$, $\dot{M}_{L,i}$, $\dot{P}_{k,U,i}$, $\dot{P}_{k,L,i}$, $\dot{Q}_{U,i}$, and $\dot{Q}_{L,i}$ which appear on the right-hand sides of the various components of this equation set. In any particular CCFM application, a treatment of these terms would include any required analysis of the diffusion of heat and mass through solids. In CCFM.VENTS, heat and mass diffusion phenomena are not treated explicitly and such analysis is not required. To explicitly include these diffusion phenomena an enriched structure of the generic equation set could be appropriate.

2.4. The Equation Set for a Specific CCFM Application

One establishes a specific application of the generic CCFM equations by identifying explicitly the algorithms used to calculate the terms $\dot{M}_{U,i}$, $\dot{M}_{L,i}$, $\dot{P}_{k,U,i}$, $\dot{P}_{k,L,i}$, $\dot{Q}_{U,i}$, and $\dot{Q}_{L,i}$ which appear on their right-hand sides. As mentioned in Section 2.1, the actual phenomena included in a simulation and the detail and sophistication with which they are modeled would distinguish one application of the CCFM generic equation set from another. The remainder of this work provides the details of the first-stage CCFM application, CCFM.VENTS.

The next section identifies and presents the algorithms for all the phenomena taken into account in CCFM.VENTS.

3. The CCFM.VENTS-Specific Equation Set: Submodel Algorithms

3.1. The Layers' Sources of Mass, Enthalpy, and Products of Combustion

In CCFM.VENTS it is assumed that there are three basic phenomena which can lead to contributions to the rates of flow of mass, enthalpy and products of combustion to the upper and lower layers of the rooms of a facility, namely, (1) a fire and its plume; (2) natural flows through vertical vents driven by room-to-room cross-vent hydrostatic pressure differences; and (3) forced-ventilation flows between pairs of rooms connected by fan/duct systems. Algorithms used to model these phenomena in CCFM.VENTS are described in detail in Sections 3.2, 3.3, and 3.4, respectively.

3.2. Plume and Heat Transfer in Rooms of Fire Origin

3.2.1. Some Basic Assumptions

Consider one of the rooms of the facility which contains a fire. This is illustrated in Figure 3.2.1. Figure 3.2.2 depicts the fire and its plume for all possible configurations during the two-layer simulation of the fire environment. Section 3.2 describes an algorithm for estimating the rates of exchange and addition of mass, enthalpy, oxygen, and other products of combustion between and to the two layers. The exchanges considered here are those which are the result of direct action of the fire/plume dynamics. The algorithm is based on the model of reference [3.2.1] for the upward mass flow rate in a buoyant point-source-driven plume. It is the same as the algorithm used in the one-room fire model, ASET [2.1.4]. Thus, it is assumed that the energy and all products of combustion released by the fire are deposited in the room by means of a small volume source. This is modeled as a point source.

The total energy-release rate of the fire, $\dot{Q}$, is specified. It is assumed that the combustion zone and the plume radiate from the source at an effective rate $\lambda_R \dot{Q}$, where λ_R is specified; thus

$$\dot{Q}_{SOURCE} = (1 - \lambda_R)\dot{Q} \qquad (3.2.1)$$

is the part of the fire's energy-release-rate which drives the convective buoyant fire plume upward.

Flaming fires exhibit λ_R's in the range $0 < \lambda_R < 0.6$, e.g., smaller values for smaller methane fires and higher values for large polystyrene fires. However, for hazardous fires over a wide range of energy release rate and involving a wide range of common groupings of combustibles, it is reasonable to approximate flame radiation by choosing $\lambda_R = 0.35$ [2.1.4]. This is taken as the default value in CCFM.VENTS.

The fire is assumed to be a source of oxygen and of (N_{PROD} - 1) other user-specified products of combustion which are taken account of in the simulation.

Following the rule of reference [3.2.2], which is useful for most fuels commonly encountered in fires, it is assumed that the rate of O_2 generation in the oxidation process, $\dot{P}_{O2,SOURCE}$, is negative (i.e., oxygen is consumed) and directly proportional to $\dot{Q}$.

$$\text{rate of } O_2 \text{ generation} = \dot{P}_{O2,SOURCE} \equiv \dot{P}_{1,SOURCE} = -F \cdot \dot{Q} \qquad (3.2.2)$$

where

$$F = 0.076(10^{-6})(\text{kg of } O_2)/J \qquad (3.2.3)$$

It is assumed that the other products of combustion are generated at specified rates $\dot{P}_{k,SOURCE}$, $k = 2$ to N_{PROD} [(unit of product k)/s]. Typically, the rate at which fuel mass is introduced to the combustion process is negligible compared to other characteristic mass flow rates of interest in the simulation, and this is assumed to be the case here.

If the lower layer is of non-zero thickness and if the fire is in the lower layer, then it is assumed that a complete description of the lower-layer room environment at the instant of interest is known. This includes the density, absolute temperature, concentration of O_2 [(kg of O_2)/(kg layer)], and concentrations of the other (N_{PROD} - 1) products of combustion [(unit of product k)/(kg layer)]. These are designated by ρ_L, T_L, $c_{O2,L} \equiv c_{1,L}$, and $c_{k,L}$, $k = 2$ to N_{PROD}, respectively. The O_2 and other product concentrations would be required only when these concentrations were actually being predicted.

The ideal gas relationship for air is assumed to be valid for the entire room environment.

The elevation of the interface separating the upper and lower layers is y_{LAYER}. The fire is located at elevation y_{FIRE}, which is assumed to be between or at the elevation of the room's floor and ceiling, y_{FLOOR} and y_{CEIL}, respectively. Consistent with the idealized point-source plume model of [3.2.1], it is appropriate to choose y_{FIRE} as the lowest elevation above the base of the combustion zone where relatively free, unrestricted, lateral entrainment of the local gas into the combustion zone or plume is possible.

Note that all elevations are relative to the same datum elevation.

It is assumed that the total fraction of $\dot{Q}$ which is lost to the bounding surfaces of the room by all modes of heat transfer is given by $\lambda_T\dot{Q}$, where λ_T is specified. The remaining portion of $\dot{Q}$ is $\dot{Q}_{TOTAL}$, i.e.,

$$\dot{Q}_{TOTAL} = (1 - \lambda_T)\dot{Q} \qquad (3.2.4)$$

This is assumed to be deposited entirely in the upper layer (except for the special Configurations 3 and 6, Figure 3.2.2, to be discussed below). When the fire is in the upper layer this is all added to the upper layer directly and there is no other enthalpy flow due to the fire. When the fire is in the lower layer, the net rate of enthalpy flow into the upper layer due to the fire is $\dot{Q}_{TOTAL}$ plus the rate of enthalpy flow associated with the gases entrained into the plume from the lower layer and deposited by the plume into the upper layer.

Some limited guidance on the choice of λ_T in the range $0.6 < \lambda_T < 0.9$ is provided in reference[2.1.4]. The default value of λ_T is taken to be 0.8 in CCFM.VENTS.

The algorithm assumes no gas-to-room-surface losses of products of combustion.

The fire-driven exchange and addition of mass, enthalpy, and products of combustion between and to the two layers can depend on the strength of the fire plume and on the relative elevations of fire and interface and interface and ceiling. At any instant, a fire scenario can fall into any one of the six configurations shown in Figure 3.2.2. The flows for each of these configurations are discussed below.

3.2.2. Fire in the Lower Layer

3.2.2.1. Interface Below the Ceiling

<u>Configuration 1</u>:

This configuration satisfies

$$y_{LAYER} - y_{FIRE} = Z > 0 \text{ and } y_{CEIL} > y_{LAYER} \tag{3.2.5}$$

and is depicted in Figure 3.2.2a.

Following reference [3.2.1], the mass flow rate in the plume as it penetrates the layer interface and enters the upper layer is estimated to be

$$\dot{M}_{PLUME} = 0.21\rho_L(gZ)^{1/2}Z^2Q^{*1/3} \tag{3.2.6}$$

$$Q^* = \dot{Q}_{SOURCE}/[\rho_L T_L C_p g^{1/2} Z^{5/2}] \tag{3.2.7}$$

where C_p is the specific heat of air at constant pressure, assumed to be constant, and g is the acceleration of gravity.

$\dot{M}_{PLUME}$ is modeled as being identical to the flow extracted by plume entrainment from the lower layer. Accordingly, the fire plume leads to the following contributions to the total rates of flow to the lower-layer of mass, $\dot{M}_L$; enthalpy, $\dot{Q}_L$; molecular oxygen, $\dot{P}_{O2,L} \equiv \dot{P}_{1,L}$; and other products of combustion, $\dot{P}_{k,L}$, $k = 2$ to N_{PROD}:

$$\dot{M}_L = - \dot{M}_{PLUME} \tag{3.2.8}$$

$$\dot{Q}_L = - \dot{M}_{PLUME} \cdot C_p \cdot T_L \tag{3.2.9}$$

$$\dot{P}_{O2,L} = - c_{O2,L} \cdot \dot{M}_{PLUME} \tag{3.2.10}$$

$$\dot{P}_{k,L} = - c_{k,L} \cdot \dot{M}_{PLUME}, \quad k = 2 \text{ to } N_{PROD} \tag{3.2.11}$$

At the interface, all of the mass, enthalpy, and products of combustion flowing in the plume, both from generation in the fire and from plume entrainment, are deposited into the upper layer. Accordingly, the fire and its plume leads to the following contributions to the total rates of flow to the upper-layer of mass, $\dot{M}_U$; enthalpy, $\dot{Q}_U$; molecular oxygen, $\dot{P}_{O2,U} \equiv \dot{P}_{1,U}$; and other products of combustion, $\dot{P}_{k,U}$:

$$\dot{M}_U = \dot{M}_{PLUME} \tag{3.2.12}$$

$$\dot{Q}_U = \dot{M}_{PLUME} \cdot C_p \cdot T_L + \dot{Q}_{TOTAL} \tag{3.2.13}$$

$$\dot{P}_{O2,U} = c_{O2,L} \cdot \dot{M}_{PLUME} - F \cdot \dot{Q} \tag{3.2.14}$$

$$\dot{P}_{k,U} = c_{k,L} \cdot \dot{M}_{PLUME} + \dot{P}_{k,SOURCE}, \quad k = 2 \text{ to } N_{PROD} \tag{3.2.15}$$

3.2.2.2. **Interface at Ceiling, Zero-Thickness Upper Layer**

This configuration is associated with an instant of time during the fire scenario when the upper layer has not yet formed or when a previously-developed upper layer has been reduced to one of zero thickness. At such a time it is important to determine, within the context of the overall two-layer zone-type approximation, whether the characteristic temperature of the plume at the ceiling above the lower-layer temperature is large enough to initiate the growth of a coherent stratified upper layer. If so, then it would be reasonable to carry out all flow-exchange calculations as in Configuration 1. This would lead to the initiation of upper-layer growth. If the characteristic temperature rise of the plume is smaller than some specified value, ΔT_{EPS}, then it is reasonable to assume that all of the plume flow is mixed back into the full-room-height lower layer. Under such a circumstance, no mass, enthalpy, or products in the plume flow would be available to initiate growth of an upper layer.

An appropriate specification of ΔT_{EPS} would depend on the fire scenario being simulated. For example, pre-ignition stratification of a room, by whatever means (e.g., due to solar heating effects), can establish near-ceiling temperatures which are several degrees K above the average room temperature. With such an initial environment it is inappropriate to suggest that the environment as modified by the fire can be described usefully by a two-layer model, unless the difference between the predicted upper and lower layer temperatures is greater than the characteristic temperature difference of the pre-ignition stratified environment. For example, if the pre-ignition temperature difference is estimated to be 5-10 K, then it may be reasonable to choose ΔT_{EPS} as, e.g., 10-20 K.

In general, it is inappropriate to take seriously a two-layer description of room fire environment unless the difference in temperature between the layers is at least of the order, of 1 K.

The ΔT_{EPS}-type of temperature-rise criterion for initiation of an upper layer is adopted here, where the value of ΔT_{EPS} in CCFM.VENTS is taken to be 1 K. The characteristic plume temperature, T_{PLUME}, is taken to be the average temperature of the plume gases at the ceiling elevation, and the characteristic temperature rise, ΔT_{PLUME}, used in the criterion is found from

$$\Delta T_{PLUME} = |T_{PLUME} - T_L| = \dot{Q}_{SOURCE}/(C_p \cdot \dot{M}_{PLUME}) \qquad (3.2.16)$$

where $\dot{Q}_{SOURCE}$ and $\dot{M}_{PLUME}$ are calculated in Eqs. (3.2.1), (3.2.6) and (3.2.7).

<u>Configuration 2</u>: Relatively Strong Plume Initiates Upper Layer Growth

This configuration satisfies

$$y_{LAYER} - y_{FIRE} = Z > 0 \text{ and } y_{CEIL} = y_{LAYER} \qquad (3.2.17)$$

$$\Delta T_{PLUME} \geq \Delta T_{EPS} \qquad (3.2.18)$$

and is depicted in Figure 3.2.2b.

The condition of Eq. (3.2.18) indicates that the plume at the ceiling is relatively strong. It is therefore assumed that growth of an upper layer will be initiated. Under these circumstances, all flow-exchange calculations are carried out as in Eqs. (3.2.8)-(3.2.15) of Configuration 1.

<u>Configuration 3</u>: Relatively Weak Plume Does Not Initiate Upper Layer Growth

This configuration satisfies

$$y_{LAYER} - y_{FIRE} = Z > 0 \text{ and } y_{CEIL} = y_{LAYER} \quad (3.2.19)$$

$$\Delta T_{PLUME} < \Delta T_{EPS} \quad (3.2.20)$$

and is depicted in Figure 3.2.2c.
The condition of Eq. (3.2.20) indicates that the plume at the ceiling is relatively weak. It is therefore assumed that growth of an upper layer is not initiated as a result of fire-generated flows. Under these circumstances, the fire simply deposits its products into the lower layer. This leads to the following contributions to the rates of change of mass, enthalpy, and products in the upper and lower layers

$$\dot{M}_L = \dot{M}_U = \dot{P}_{O2,U} = \dot{P}_{k,U} = \dot{Q}_U = 0, \; k = 2 \text{ to } N_{PROD} \quad (3.2.21)$$

$$\dot{Q}_L = \dot{Q}_{TOTAL} \quad (3.2.22)$$

$$\dot{P}_{O2,L} = - F \cdot \dot{Q} \quad (3.2.23)$$

$$\dot{P}_{k,L} = \dot{P}_{k,SOURCE}, \; k = 2 \text{ to } N_{PROD} \quad (3.2.24)$$

3.2.3. **Fire in Upper Layer**

<u>Configuration 4</u>:

This configuration satisfies

$$y_{LAYER} - y_{FIRE} = Z < 0 \quad (3.2.25)$$

and is depicted in Figure 3.2.2d.

As indicated in the figure, although a fire plume will be formed in the upper layer it is assumed that the plume does not lead to any exchanges of mass and products between the layers. The fire simply deposits its products into the upper layer. This leads to the following contributions to the rates of change of mass, enthalpy, and products in the upper and lower layers

$$\dot{M}_L = \dot{M}_U = \dot{P}_{O2,L} = \dot{P}_{k,L} = \dot{Q}_L = 0, \; k = 2 \text{ to } N_{PROD} \tag{3.2.26}$$

$$\dot{Q}_U = \dot{Q}_{TOTAL} \tag{3.2.27}$$

$$\dot{P}_{O2,U} = - F \cdot \dot{Q} \tag{3.2.28}$$

$$\dot{P}_{k,U} = \dot{P}_{k,SOURCE}, \; k = 2 \text{ to } N_{PROD} \tag{3.2.29}$$

3.2.4. Fire at the Layer Interface

During the course of a simulation it is possible that the elevations of the fire and layer interface coincide exactly. When this occurs, $y_{LAYER} - y_{FIRE} = Z = 0$ and, according to Eqs. (3.2.6) and (3.2.7), $\dot{M}_{PLUME} = 0$. Two subcases of this configuration have to be considered.

3.2.4.1. Fire Below the Ceiling

Configuration 5:

This configuration satisfies

$$y_{LAYER} - y_{FIRE} = Z = 0 \text{ and } y_{FIRE} < y_{CEILING} \tag{3.2.30}$$

and is depicted in Figure 3.2.2e.

This is the case where there is a non-zero upper layer and the elevation of the fire and of the interface are identical.

From Eqs. (3.2.6) and (3.2.7) $\dot{M}_{PLUME} = 0$. Then the flow contributions predicted by the equations of Configurations 1 [Eqs. (3.2.8)-(3.2.15)] and 4 [Eqs. (3.2.26)-(3.2.29)] are identical and either set is applicable.

3.2.4.2. Fire at the Ceiling

Configuration 6:

This configuration satisfies

$$y_{LAYER} - y_{FIRE} = Z = 0 \text{ and } y_{FIRE} = y_{CEILING} \tag{3.2.31}$$

and is depicted in Figure 3.2.2f.

This is the case where there is a zero upper layer and the elevations of the fire, the interface, and the ceiling are all identical. Under these circumstances and for the plume model adopted here, no plume exists to entrain mass from the lower layer and to initiate growth of an upper layer. It is therefore assumed that, as in Configuration 3, growth of an upper layer will not be initiated as a result of fire-generated flows and that the fire simply deposits its products into the lower layer. This leads to contributions to the rates of change of mass, enthalpy, and products in the upper and lower layers which are identical to those prescribed in Eqs. (3.2.21)-(3.2.24).

3.2.5. The Algorithm PLUGO and Its Associated Subroutine

The algorithm described above in Sections 3.2.1 - 3.2.4 for calculating fire-plume-generated flows and heat transfer has been named PLUGO. A concise presentation of PLUGO and its associated FORTRAN subroutine appears in Part III [1.1.2] of this work.

3.3. Natural Vent Flows and Heat Transfer

3.3.1. Three Stages of the Calculation

Consider a pair of adjacent rooms of a facility involved a fire scenario. Room pairs considered here are those which have a common vertical wall segment with an arbitrary, non-zero number of penetrations, referred to here as vents. Described in Section 3.3 is an algorithm for estimating the rates of exchange of mass, enthalpy, oxygen, and other products of combustion through the vents and between the layers of the two rooms. The exchanges considered here are the result of vent flows driven only by room-to-room cross-vent hydrostatic pressure differences. Only rectangular vents with horizontal and vertical boundaries are considered.

At any instant, the complete vent-flow calculation is carried out in three stages. In the first stage, all parameters are established for a calculation of the room-to-room hydrostatic pressure difference at an arbitrary elevation of the common-wall segment. This pressure difference drives the room-to-room vent flows to be studied here. In the second and third stages of the calculation, the individual vents in the wall segment are considered one by one. The second stage determines all characteristics of any particular vent flow. As will be discussed below, such a flow can involve from one to six, contiguous, horizontal slabs of uniform-property, unidirectional flows. For each such slab, the third stage determines the portion of the flow going to each of the two receiving-room layers and the rate of extraction from its single source-room layer.

The natural vent flow and heat transfer model described in Section 3.3 is based on a consolidation of and extensions to ideas presented in references

[2.1.1], [2.1.2], [2.1.4], and [3.3.1-3.3.5]. These references will be identified at appropriate places in the text. It should also be noted that the basic ideas used here for calculating vent flow rates under typical conditions of relatively low cross-vent pressure difference have also been used in all vent flow calculations of the models of references [2.1.1-2.1.12].

3.3.2. Specification of Geometry and Fire Environment of the Room Pair

Designate two adjacent rooms of interest as rooms 1 and 2, and refer to Figure 3.3.1. The index i will be used below to indicate physical characteristics and layer properties of room i, i = 1 or 2.

The geometric characteristics of the two rooms required for the present calculation are the elevations of their floors and ceilings, $y_{FLOOR,i}$ and $y_{CEIL,i}$, respectively.

In each room the instantaneous states of the layers are specified by the elevation of the interfaces, $y_{LAYER,i}$, separating the upper and lower layers and by the properties of the layers, $\rho_{U,i}$, $\rho_{L,i}$, $T_{U,i}$, $T_{L,i}$, $c_{O2,U,i}$, $c_{O2,L,i}$, $c_{k,U,i}$, and $c_{k,L,i}$, k = 2 to N_{PROD}, as defined in Section 2.

At instants of time when there is no upper layer [lower layer], i.e., when $y_{LAYER,i} = y_{CEIL,i}$ [$y_{LAYER,i} = y_{FLOOR,i}$], upper-layer [lower-layer] properties are not used in the calculation. Also, as in Section 3.2, O_2 and other product concentrations would be required only when the simulation under consideration is actually being used to predict these concentrations.

The final specifications of the environment are the $\delta p_{FLOOR,i}$ for the two rooms. As defined in Eq. (2.3.1), these are the differences between the absolute hydrostatic pressures at the floor of each room and some fixed, absolute, hydrostatic datum pressure, p_{DATUM}. As discussed in Section 2.3.1, the $\delta p_{FLOOR,i}$ are the solution pressure variables used in the basic equation set for room i.

One of the two rooms connected by a vent can be an outside-environment space or "room." Local to any single outside-exposed vent, the hydrostatic pressure in the outside space is computed in the same way as in the inside room. In the outside space, however, the vent is always submerged by a "lower layer" of unlimited extent and of uniform, specified properties analogous to $\rho_{L,i}$, $T_{L,i}$, $c_{O2,L,i}$, and the $c_{k,L,i}$, i.e., the layer-interface elevation, $y_{LAYER,i}$, for the outside space or "room" is indefinitely large. In order to fix the pressure calculation in the outside space, a reference outside-space elevation, analogous to $y_{FLOOR,i}$ for the inside rooms, and a pressure at this reference elevation, analogous to δpFLOOR,i for the inside rooms, must be specified.

In the discussion to follow, when one of the facility "rooms" is an outside space, room variables identified should be substituted by analogous variables of the outside space.

As in Section 3.2, in Section 3.3 all elevations are relative to the same datum elevation.

3.3.3. First Stage of the Calculation: Parameters to Determine the Cross-Vent Pressure Difference at an Arbitrary Elevation of the Common-wall Segment

At an arbitrary elevation, y, in one of the rooms, $p_i(y)$ is calculated from

$$p_i(y) = \delta p_{FLOOR,i} + \delta p_i(y) + p_{DATUM} \tag{3.3.1}$$

where $\delta p_i(y)$, the difference between the absolute hydrostatic pressure at y and at $y_{FLOOR,i}$, is obtained from hydrostatics to be

$$\delta p_i(y) = \begin{cases} -\rho_{L,i}g(y - y_{FLOOR,i}), & y_{FLOOR,i} \le y \le y_{LAYER,i}; \\ -\rho_{L,i}g(y_{LAYER,i} - y_{FLOOR,i}) - \rho_{U,i}g(y - y_{LAYER,i}), & y_{LAYER,i} < y \le y_{CEIL,i} \end{cases} \tag{3.3.2}$$

and where g is the acceleration of gravity.

In general, the above distributions, $\delta p_i(y)$, would involve two linear functions of elevation for each of the two rooms. This is depicted at the top of Figure 3.3.2. One function describes $\delta p_i(y)$ in the lower layer, from the floor of the room to the interface, and the other in the upper layer, from the interface to the ceiling. At the interface, $\delta p_i(y)$ is continuous, but its slope is discontinuous.

At a given y of the common-wall segment, the difference between the pressures in the two rooms, $\Delta p_{1,2}$, is defined by

$$\Delta p_{1,2} \equiv p_1(y) - p_2(y) \tag{3.3.3}$$

Using Eqs. (2.3.1), (3.3.1)-(3.3.3), it is found that $\Delta p_{1,2}$ can be calculated from

$$\Delta p_{1,2} = (\delta p_{FLOOR,1} - \delta p_{FLOOR,2}) + [\delta p_1(y) - \delta p_2(y)], \tag{3.3.4}$$

$$y_{MIN} = \max(y_{FLOOR,1}, y_{FLOOR,2}) \le y \le \min(y_{CEIL,1}, y_{CEIL,2}) = y_{MAX}$$

Note that Eq. (3.3.4) is only valid at elevations at or between the lower- and upper-elevation limits of the common-wall segment, y_{MIN} and y_{MAX}, respectively.

The Eq. (3.3.4)-formulation for calculating $\Delta p_{1,2}$ reveals the benefit of using the relative pressure, $\delta p_{FLOOR,i}$, instead of the absolute pressure, $p_i(y = y_{FLOOR,i})$, as the solution pressure variable in the basic equation set discussed in Section 2. If $p_i(y = y_{FLOOR,i})$ was used, then $\Delta p_{1,2}$ would have to be calculated directly from Eq. (3.3.3). This would involve the difference of the two absolute pressures, $p_1(y = y_{FLOOR,1})$ and $p_2(y = y_{FLOOR,2})$. Since it would be typical for these two values to be identical to each other to within four or five significant figures, there would be a corresponding loss in the number of significant figures in the computed value of $\Delta p_{1,2}$, i.e., as mentioned earlier, absolute pressures are typically of the order of 100,000 pascals while pressure differences throughout entire facilities are typically of the order of a few or, at most, several tens of pascals. This would, in turn, lead to an unnecessary loss in accuracy in the vent-flow rates, to be determined below from $\Delta p_{1,2}$. By using $\delta p_{FLOOR,i}$ as the solution pressure variable and by introducing an appropriate value for p_{DATUM} in Eq. (3.3.1), the significant figures which would be lost when calculating $\Delta p_{1,2}$ from Eq. (3.3.3) is regained by calculating it from Eq. (3.3.4).

The bracketed term of Eq. (3.3.4) involves the difference of the two $\delta p_i(y)$ functions where each one involves up to two linear segments continuous in the interval $y_{MIN} \le y \le y_{MAX}$. Therefore, $\Delta p_{1,2}$ is also continuous in this interval and is made up of from one to three linear segments. The vertical bounds of these segments involve a minimum of two and a maximum of four discrete elevations: y_{MIN} at the bottom, y_{MAX}, at the top, and, if they lie in between, either or both of the $y_{LAYER,i}$. It is a simple matter to calculate from Eq. (3.3.4) the value of $\Delta p_{1,2}$ which corresponds to each of these N_{WELEV} wall elevations, where $2 \le N_{WELEV} \le 4$. Assuming that this is done, the unique set of points, $[y_N, \Delta p_{1,2}(y_N)]$, $N = 1$ to N_{WELEV}, which define the $\Delta p_{1,2}$ segments is then ordered according to monotonically increasing y_N.

In general, each of the one to three linear segments of $\Delta p_{1,2}$ can have a slope of arbitrary magnitude and sign. For this reason, it is possible for each to have a zero $\Delta p_{1,2}$ value inside its vertical y-range of applicability. For any particular segment, it is a simple matter to determine if such a zero exists. This could be done, for example, by establishing whether or not the now-known $\Delta p_{1,2}$ values at the segment endpoints are both non-zero and of different sign. If it is determined that a segment has an elevation where $\Delta p_{1,2} = 0$, then this elevation is calculated and, together with its corresponding $\Delta p_{1,2} = 0$ value, it is sorted into the previous $[y_N, \Delta p_{1,2}(y_N)]$ set. After all zeros have been determined, the resulting $[y_N, \Delta p_{1,2}(y_N)]$ set would involve N_{WELEV} points, where N_{WELEV} now satisfies $2 \le N_{WELEV} \le 7$.

The final N_{WELEV} set of points identifies end-points of one to six, uniform-sign, contiguous segments of $\Delta p_{1,2}$. These segments are linear in y and they determine completely the distribution of $\Delta p_{1,2}$ which is continuous across the entire common-wall segment.

Figure 3.3.2 illustrates possible $\Delta p_{1,2}$ distributions with from one to six segments and with corresponding endpoints $[y_N, \Delta p_{1,2}(y_N)]$, $1 \le N \le N_{WELEV} = 2$ to 7.

3.3.4. Second Stage of the Calculation: Characteristics of a Vent Flow

3.3.4.1. The Uniform-Property Flow Slabs

Consider an arbitrary vent in the above common-wall segment. Its width and upper and lower bounds are specified as b, y_{VTOP} and y_{VBOT}, respectively, where $y_{VTOP} - y_{VBOT} > 0$. The cross-vent $\Delta p_{1,2}$ distribution is that portion of the $\Delta p_{1,2}$ distribution for the common-wall segment, given by Eq. (3.3.4), which lies in the interval $y_{VBOT} \le y \le y_{VTOP}$.

To obtain the end-points of the $\Delta p_{1,2}$ distribution for the vent: use Eq. (3.3.4) to calculate the two $\Delta p_{1,2}$'s corresponding to y_{VBOT} and y_{VTOP}, sort the resulting two $[y, \Delta p_{1,2}]$ points into the $[y_N, \Delta p_{1,2}(y_N)]$ set for the entire common-wall segment, and eliminate any points of the resulting set having $y_N \le y_{VBOT}$ and $y_N \ge y_{VTOP}$. Non-unique points of the set are also eliminated, e.g., if $y_{VBOT} = y_{FLOOR,1}$. The resulting set of vent elevations would have N_{VELEV} points, where N_{VELEV} satisfies $2 \le N_{VELEV} \le 7$.

The final N_{VELEV} points identify end-points of one to six, uniform-sign, contiguous segments of $\Delta p_{1,2}$ which determine the distribution of $\Delta p_{1,2}$ across the vent.

At a given y, the direction and rate at which flow is driven through the vent is determined locally by the sign and magnitude of $\Delta p_{1,2}$. If $\Delta p_{1,2} > 0$ for a given segment of the $\Delta p_{1,2}$ distribution, then, throughout this segment, the flow will be from room 1 to room 2 and the source of the flow will be one of the one or two uniform-property layers of room 1. If $\Delta p_{1,2} < 0$ in the segment, then the flow is reversed and its source will be one of the one or two layers of room 2. The uniform-property flow corresponding to a single $\Delta p_{1,2}$ segment is referred to here as a flow slab.

For a generic vent, Figure 3.3.3 illustrates possible $\Delta p_{1,2}$ distributions with from one to six segments and N_{VELEV} corresponding endpoints. In the figure, the direction of the flow-slab velocity, corresponding to each $\Delta p_{1,2}$ segment, and actual velocity distributions are indicated by arrows.

3.3.4.2. Mass Flow Rate in the Flow Slab

Number the flow slabs through a vent from the lowest (N = 1) to the highest ($N = N_{SLAB} = N_{VELEV} - 1 \le 6$). Then, according to the above-implemented sorting procedure the bottom and top elevation of an arbitrary slab, N, will be y_N and y_{N+1}, respectively. Attention here is confined to the problem of estimating the rate of cross-vent flow in slab N.

Between y_N and y_{N+1}, the direction of the flow in the slab and the uniform density, temperature, and concentrations of products of combustion of the flow upstream of the vent are fixed. Also, throughout the depth of the slab, p_1, p_2, and $\Delta p_{1,2}$ are each linear in y. $\Delta p_{1,2}$ can be zero at the bottom or top of a slab, and it can be identically zero, i.e., a slab with zero cross-vent flow, but $\Delta p_{1,2}$ cannot change signs in the slab.

Identify the flow direction of the slab by I_{DIR} = 1, 0, or -1, according to whether the flow is from room 1 to room 2 ($\Delta p_{1,2} > 0$ in the slab), zero ($\Delta p_{1,2} \equiv 0$ in the slab), or room 2 to room 1 ($\Delta p_{1,2} < 0$ in the slab), respectively. If the flow in the slab is zero then no further consideration is required. Therefore, assume that the arbitrary slab under consideration has a non-zero flow.

With complete generality, assume that the flow in the slab is from room 1 to room 2. (If the flow is actually from room 2 to room 1, then re-number for now the pair of rooms under consideration.) Also, designate the properties of the slab's room-1 source layer with the subscript 1, i.e., the density, temperature, oxygen and product k concentrations are ρ_1, T_1, $c_{O2,1}$, and $c_{k,1}$, respectively.
Define $\Delta\rho$ and Δp according to

$$\Delta\rho \equiv \rho_1 - \rho_2 \qquad (3.3.5)$$

$$\Delta p(y) \equiv \Delta p_{1,2}(y) = p_1(y) - p_2(y) \geq 0 \qquad (3.3.6)$$

where ρ_1 and ρ_2 are the uniform densities in rooms 1 and 2, respectively, at the height of the slab. (Recall that while Eq. (3.3.6) is similar to Eq. (3.3.3), the rooms have been re-numbered so that the inequality of Eq. (3.3.6) is valid.) Define Δp_N, p_N and Δp_{N+1}, p_{N+1} as the previously obtained values of Δp, p_1 at $y = y_N$ and y_{N+1}, respectively. Define also

$$\begin{aligned} \epsilon(y) &\equiv \Delta p(y)/p_1(y) \equiv 1 - x(y) \geq 0 \\ x(y) &\equiv p_2(y)/p_1(y) \equiv 1 - \epsilon(y) \end{aligned} \qquad (3.3.7)$$

In typical compartment fire scenarios, cross-vent pressure differences, which are relatively small (compared to p_1) and lead to relatively low-speed flow velocities (compard to the speed of sound), satisfy

$$0 < \Delta p/p_1 = \epsilon(y) << 1 \quad \text{for "typical" compartment fires} \qquad (3.3.8)$$

Fire scenarios involving flow slabs with relatively large cross-vent pressures and associated high-speed flow velocities will have ϵ's which do not satisfy Eq. (3.3.8). Such moderate-size ϵ's will lead to single-slab vent flows of the type depicted in Figure 3.3.3(a). The Δp distributions for such moderate-ϵ flows will satisfy $|\Delta p_N - \Delta p_{N+1}|/\min(\Delta p_N, \Delta p_{N+1}) << 1$.

Define $\bar{y}$ as the elevation of the middle of the slab, and $\bar{\epsilon}$ as the value of ϵ at $\bar{y}$, i.e.,

$$\bar{y} = (y_N + y_{N+1})/2$$
$$\bar{\epsilon} \equiv \epsilon(y = \bar{y}) \equiv 1 - \bar{x} = (\Delta p_N + \Delta p_{N+1})/(p_N + p_{N+1}) \quad (3.3.9)$$

Assuming isentropic flow and adopting the traditional approximation that the thermodynamic state of the gas flowing through the vent varies, at a given y, only in the streamwise direction, the total rate of mass flow in the slab, $\dot{M}_{SLAB}$, can be estimated from (see reference [3.3.1])

$$\dot{M}_{SLAB} = b\bar{C}\bar{w}[(8\rho_1)^{1/2}/3](y_{N+1} - y_N) \cdot$$
$$[(|\Delta p_N| + |\Delta p_N \Delta p_{N+1}|^{1/2} + |\Delta p_{N+1}|)/(|\Delta p_N|^{1/2} + |\Delta p_{N+1}|^{1/2})] \quad (3.3.10)$$

where

$$\bar{w} \equiv w(\bar{x}) = w(1 - \bar{\epsilon}) \; ; \; \bar{C} \equiv C(\bar{x}) = C(1 - \bar{\epsilon}) \quad (3.3.11)$$

and where w and C are given by

$$w(x) = f(x)/[2(1 - x)]^{1/2} \quad (3.3.12)$$

$$f(x) = \begin{cases} \{[2\gamma/(\gamma - 1)]x^{2/\gamma}[1 - x^{(\gamma-1)/\gamma}]\}^{1/2} & \text{for } x \geq [2/(\gamma + 1)]^{\gamma/(\gamma-1)} \\ \{\gamma[2/(\gamma + 1)]^{(\gamma+1)/(\gamma-1)}\}^{1/2} & \text{for } x \leq [2/(\gamma + 1)]^{\gamma/(\gamma-1)} \end{cases} \quad (3.3.13)$$

$$C(x) = 0.68x + 0.85(1 - x) = 0.85 - 0.17x \; ; \; 0 \leq x \leq 1 \quad (3.3.14)$$

In Eq. (3.3.13), γ, the ratio of specific heats of the flowing gas, taken to have the properties of air, is 1.40.

In the above, C is a flow coefficient which depends generally on Reynolds number and x. For perfectly isentropic flow, C = 1. For real nozzles, C can be very close to 1, of the order of 0.99, for large "pipe" Reynolds number flows of 10^6 or more [3.3.2, p.99]. For sharp-edged orifices, C = C(x) and is approximately linear with x, ranging from 0.68 at x = 1 to 0.85 at x = 0.

From Eq. (3.3.7) it is clear that a scenario where the pressure ratio x is close to 0 corresponds to a situation where the absolute pressure in room 1 is several times greater than that in room 2. This is well below the value $x = 0.528$, required to initiate choked flow through the vent. For orifice-like openings typical of vents in compartment fires, x is close to 1 and $C \approx 0.68$ [3.3.3]. It is reasonable to approximate C(x) by Eq. (3.3.14) unless a more precise description of C is known for some particular vent configuration of interest.

The following expansion is useful when computing w for small ϵ

$$\lim_{x \to 1} w(x) = \lim_{\epsilon \to 0} w(1 - \epsilon) = 1 - [3/(4\gamma)]\epsilon + O(\epsilon^2) \qquad (3.3.15)$$

When $\bar{\epsilon} = 1 - \bar{x} = 0$, i.e., $\tilde{C} = C_{INCOMPRESSIBLE}$ and $\tilde{w} = 1$, Eq. (3.3.10) is identical to the small-cross-vent-pressure-difference flow equation presented in references [3.3.3] and [2.1.2]. In this form it is also equivalent to the flow calculations described in [3.3.4] and in most of the models of [2.1.1]-[2.1.12]. Thus, a simple interpretation of Eq. (3.3.10) is that when compressibility effects are arbitrarily strong or weak, the compartment fire-generated flow rate of a slab of flow, originating from a uniform stagnation source and passing through a constant-width vertical vent, can be computed by ignoring elevation-related differences of compressibility in the slab and by using the characteristic mass flux for compressible nozzle/orifice flow which corresponds to the mid-slab cross-vent pressure difference.

3.3.4.3. Other Flow Rates of the Flow Slab

With $\dot{M}_{SLAB}$ from Eq. (3.3.10), and with the known values of T_1, $c_{O2,1}$, and $c_{k,1}$, the rates of flow of enthalpy, oxygen, and product of combustion k in the slab, which are designated by $\dot{Q}_{SLAB}$, $\dot{P}_{O2,SLAB}$, and $\dot{P}_{k,SLAB}$, respectively, are obtained from

$$\dot{Q}_{SLAB} = \dot{M}_{SLAB} \cdot C_p \cdot T_1 \qquad (3.3.16)$$

$$\dot{P}_{O2,SLAB} = \dot{M}_{SLAB} \cdot c_{O2,1} \qquad (3.3.17)$$

$$\dot{P}_{k,SLAB} = \dot{M}_{SLAB} \cdot c_{k,1} \qquad (3.3.18)$$

These flows come from the source layer in room 1. Subsequent to the slab flow entry to room 2, these flows are divided and deposited into the two layers in room 2 according to the rule to be specified below in Section 3.3.5.

3.3.4.4. Properties of the Penetrating Flow

In order to use Eq. (3.3.10) in any particular room fire model it is necessary to know the properties of the penetrating flow as it enters room 2. With such information in hand it would then be possible to invoke the model's adopted rule for dividing and depositing this incoming flow into the room's upper and lower layers. The desired result is obtained by observing that as the flow passes through the penetrations it maintains an approximately constant total enthalpy, i.e., the flow is essentially adiabatic. Thus, assuming deceleration of the flow to a negligible horizontal velocity prior to mixing in the receiving room, the temperature at this point, T_{PEN}, will be identical to T_1.

$$T_{PEN} = T_1 \tag{3.3.19}$$

Using this result, the density after penetration but before mixing, ρ_{PEN}, can be obtained from the perfect gas law.

$$\rho_{PEN} = \rho_1 \cdot (p_2/p_1) = \rho_1 \cdot x \tag{3.3.20}$$

For typical fire scenarios, where the cross-vent pressure ratio, x, is close to 1, the above leads to the expected result that the properties of the penetrating flow are identical to its properties in room 1.

Conservation of species leads to

$$\begin{aligned} c_{O2,PEN} &= c_{O2,1} \\ c_{k,PEN} &= c_{k,1} \end{aligned} \tag{3.3.21}$$

where, again, the subscript PEN indicates a property of the slab flow in the receiving room after penetration and deceleration, but before significant mixing.

3.3.4.5. A Characteristic Elevation of the Flow Slab

As the flow slab enters the receiving room, possible rules for its distribution will depend generally on a characteristic elevation of the slab. Several choices for this elevation are available directly, viz., the top, bottom, or midpoint. Another possible choice is y_{SLAB}, the centroid of the distribution of slab N's entering horizontal-velocity, or -momentum profile, i.e.,

$$y_{SLAB} \equiv \int_{y_N}^{y_{N+1}} \rho v y dy \Big/ \int_{y_N}^{y_{N+1}} \rho v dy \approx \int_{y_N}^{y_{N+1}} v y dy \Big/ \int_{y_N}^{y_{N+1}} v dy \qquad (3.3.22)$$

where ρ is the near-uniform density and $v = v(y)$ is the velocity distribution of the flow slab as it enters room 2. To the extent that the horizontal penetration of a slab into the receiving room is dependent on its horizontal momentum, y_{SLAB} may be preferable to other characteristic elevations as a measure of the elevation of its flow as it is projected into the receiving room by its horizontal momentum.

Throughout the height of the slab

$$v(y) = \lambda |\Delta p(y)|^{1/2} \qquad (3.3.23)$$

for some constant λ, where

$$\Delta p(y) = A + By \qquad (3.3.24)$$

In Eq. (3.3.24), A and B can be determined from the known values of y_N, Δp_N and y_{N+1}, Δp_{N+1}. Then y can then be expressed as a function of Δp:

$$y = [y_{N+1}(\Delta p - \Delta p_N) - y_N(\Delta p - \Delta p_{N+1})]/(\Delta p_{N+1} - \Delta p_N) \qquad (3.3.25)$$

$$dy = [(y_{N+1} - y_N)/(\Delta p_{N+1} - \Delta p_N)]d(\Delta p) \qquad (3.3.26)$$

Eqs. (3.3.23), (3.3.25), and (3.3.26) are now used to change the variable of integration on the right side of Eq. (3.3.22) from y to Δp. Carrying out the integration leads to

$$y_{SLAB} = [(3/5)(\Delta p_{N+1}{}^{5/2} - \Delta p_N{}^{5/2})(y_{N+1} - y_N)/(\Delta p_{N+1}{}^{3/2} - \Delta p_N{}^{3/2}) + (\Delta p_{N+1} y_N - \Delta p_N y_{N+1})]/(\Delta p_{N+1} - \Delta p_N) \qquad (3.3.27)$$

When $\Delta p_{N+1} - \Delta p_N \rightarrow 0$, i.e., the velocity profile across the height of the slab is relatively uniform, an analysis of Eq. (3.3.27) yields the expected result that the centroid of the momentum profile is at the mid-elevation of the slab, i.e.,

$$\lim_{(\Delta p_{N+1} - \Delta p_N) \to 0} y_{SLAB} = (y_{N+1} + y_N)/2 \quad (3.3.28)$$

When computing y_{SLAB}, Eq. (3.3.28) should be used instead of Eq. (3.3.27) when the removable singularity of Eq. (3.3.27), at the limit $(\Delta p_{N+1} - \Delta p_N) \to 0$, is being approached.

3.3.4.6. Completing the Second Stage of the Calculation

From the results of Sections 3.3.4.2-3.3.4.5 the following properties of arbitrary flow slab N, can be calculated:

I_{DIR}, $\dot{M}_{SLAB}$, $\dot{Q}_{SLAB}$, $\dot{P}_{O2,SLAB}$, $\dot{P}_{k,SLAB}$, y_{SLAB}, T_{PEN}, ρ_{PEN}, $c_{O2,PEN}$, and $c_{k,PEN}$

The second stage of the calculation is completed by calculating this array of properties for each of the N_{SLAB} slabs of the vent flow under consideration.

3.3.5. Third Stage of the Calculation: Distribution of the Slab Flows to the Receiving Layers and Rate of Extraction from the Source Layers

3.3.5.1. General Aspects of the Rule for Distributing the Slab Flows

The third and final stage of the calculation determines the contributions of all the slab flows of a vent to the net rates of flow of mass, enthalpy, oxygen, and other products of combustion in the upper and lower layer of each of the two rooms. These are the net rates of flow, $\dot{M}_{U,i}$, $\dot{Q}_{U,i}$, $\dot{P}_{O2,U,i}$, $\dot{P}_{k,U,i}$, $\dot{M}_{L,i}$, $\dot{Q}_{L,i}$, $\dot{P}_{O2,L,i}$, and $\dot{P}_{k,L,i}$, discussed in Section 2 and required at any instant in the calculation of the right-hand-sides of Eqs. 2.3.2 - 2.3.8 for each room i of the simulation. The contributions are determined one flow slab at a time.

A flow slab originates from a single layer of the source room. With the now-known properties of the flow slab, its contributions to the net rates of flow in the source room can immediately be taken account of. For example, the instantaneous net rate of change of mass of the source layer is reduced by $\dot{M}_{SLAB}$, while that of the other layer of the source room is unaffected by the flow.

As a flow enters the receiving room it is assumed to be deposited entirely into one of the two layers or to be divided between them. The rule for apportioning the flow is based on an extension of a simple scheme, proposed in reference [3.3.5]. In determining the net enthalpy flow rate deposition, a rule is adopted which takes account of heat transfer to the walls of the room. This rule is based on an extension of ideas proposed in reference [2.1.1] and used in reference [2.1.4]. These rules will be described below.

The rule of apportioning the slab's mass, oxygen, and product of combustion flow rates is based on the temperature of the penetrating flow relative to the temperature of the receiving room's upper and lower layers. The rule addresses the special scenarios, analogous to those treated in Section 3.2.2.2, when it is not reasonable to simulate the otherwise expected initiation of upper- or lower-layer growth from zero thickness, because the magnitude of the difference between the slab temperature and that of the existing layer is smaller than some specified (relatively small) value, ΔT_{EPS}.

In addition to the latter measures of relative buoyancy, the rule for apportioning the slab's enthalpy flow rate and determining the heat transfer to the surfaces of the receiving room will depend explicitly on T_R, the temperature of the layer in the receiving room which includes the elevation y_{SLAB}, e.g., $T_R = T_{U,iREC}$ if $y_{SLAB} > y_{LAYER,iREC}$.

Designate the fraction of the flow slab deposited into the upper and lower layers as F_U and F_L, respectively. Let iREC = 1 or 2 be the value of i for the receiving room.

The basic rule adopted here for estimating the values of F_U and F_L is described below for three possible categories of interface configuration.

3.3.5.2. Interface in the Receiving Room Between the Floor and the Ceiling

These configurations involve upper and lower layers which are both of non-zero thickness. They satisfy

$$y_{FLOOR,iREC} < y_{LAYER,iREC} < y_{CEIL,iREC} \qquad (3.3.29)$$

Three temperature categories are distinguished for these configurations.

Temperature Category 1: Penetration Temperature Greater than that of the Upper Layer

This category satisfies:

$$T_{PEN} > T_{U,iREC} \qquad (3.3.30)$$

Here, the slab flow is upward-buoyant relative to the upper layer, and it is assumed that the entire slab flow, with its oxygen and products of combustion is deposited there. Thus,

$$F_U = 1. \text{ and } F_L = 0. \qquad (3.3.31)$$

Temperature Category 2: Penetration Temperature Less than that of the Lower Layer

This category satisfies:

$$T_{PEN} < T_{L,iREC} \tag{3.3.32}$$

Here, the slab flow is downward-buoyant relative to the lower layer, and it is assumed that its entire slab flow, with its oxygen and products of combustion is deposited there. Thus,

$$F_U = 0. \text{ and } F_L = 1. \tag{3.3.33}$$

Temperature Category 3: Penetration Temperature at or between those of the Upper and Lower Layers

This category satisfies:

$$T_{L,iREC} \leq T_{PEN} \leq T_{U,iREC} \tag{3.3.34}$$

Here, the slab flow is neutral or upward-buoyant relative to the lower layer, and neutral or downward-buoyant relative to the upper layer. Here, the adopted apportionment rule is that the slab flow is divided and deposited into the two layers in direct proportion to the temperature differences. In particular,

$$\begin{aligned} F_U &= (T_{PEN} - T_{L,iREC})/(T_{U,iREC} - T_{L,iREC}) \\ F_L &= (T_{U,iREC} - T_{PEN})/(T_{U,iREC} - T_{L,iREC}) \end{aligned} \tag{3.3.35}$$

3.3.5.3. Zero-Thickness Upper Layer in the Receiving Room

For this configuration the slab elevation is always within the elevation range of the lower layer which fills the room.

$$y_{SLAB} < y_{LAYER,iREC} = y_{CEIL,iREC} \tag{3.3.36}$$

Two temperature categories are distinguished.

Temperature Category 1: Relatively Strongly-Upward-Buoyant Slab Flow

This category satisfies:

$$0 < \Delta T_{EPS} \leq T_{PEN} - T_{L,iREC} \tag{3.3.37}$$

Here, the entire slab flow is deposited in a newly-initiated upper layer, and F_U and F_L are calculated according to Eq. (3.3.31).

Temperature Category 2: Relatively Weakly-Upward-Buoyant, Neutrally- or Downward-Buoyant Slab Flow

This category satisfies:

$$T_{PEN} - T_{L,iREC} < \Delta T_{EPS} \tag{3.3.38}$$

Here, the entire slab flow is deposited into the existing lower layer and F_U and F_L are calculated according to Eq. (3.3.33).

3.3.5.4. Zero-Thickness Lower Layer in the Receiving Room

For this configuration the slab elevation is always within the elevation range of the upper layer which fills the room.

$$y_{LAYER,iREC} = y_{FLOOR,iREC} < y_{SLAB} \tag{3.3.39}$$

Two temperature categories are distinguished.

Temperature Category 1: Relatively Strongly-Downward-Buoyant Slab Flow

This category satisfies:

$$0 < \Delta T_{EPS} \leq T_{U,iREC} - T_{PEN} \tag{3.3.40}$$

Here, the entire slab flow is deposited in a newly-initiated lower layer, and F_U and F_L are calculated according to Eq. (3.3.33).

Temperature Category 2: Relatively Weakly-Downward-Buoyant, Neutrally- or Upward-Buoyant Slab Flow

This category satisfies:

$$T_{U,iREC} - T_{PEN} < \Delta T_{EPS} \qquad (3.3.41)$$

Here, the entire slab flow is deposited into the existing upper layer and F_U and F_L are calculated according to Eq. (3.3.31).

3.3.5.5. Rule for Enthalpy Deposition and Heat Transfer to Room Surfaces

After entering the receiving room, but before significant mixing there, the slab flow, at temperature T_{PEN}, is surrounded by a layer environment at temperature T_R.

The total enthalpy flow rate of the slab, $\dot{Q}_{SLAB}$, is first assumed to be divided and distributed to the upper and lower layers as described in Sections 3.3.5.2 - 3.3.5.4. Then it is assumed that a portion of $\dot{Q}_{SLAB}$ is transferred to the surfaces of the receiving room. The portion transferred is assumed to be a specified fraction, λ_V, of the "enthalpy of buoyancy," defined as the enthalpy flow rate of the slab calculated relative to the temperature difference $T_{PEN} - T_R$.

$$\text{"enthalpy of buoyancy"} = \dot{M}_{SLAB} \cdot C_p \cdot (T_{PEN} - T_R)$$

$$= \dot{Q}_{SLAB} \cdot (1 - T_R/T_{PEN}) \qquad (3.3.42)$$

This "enthalpy of buoyancy" of the slab is the actual source of relative local upward-buoyancy (if the enthalpy of buoyancy is > 0) or downward-buoyancy (if the enthalpy of buoyancy is < 0) of the slab in the receiving room at elevation y_{SLAB}. This is the buoyancy which leads to the distribution of the slab flow, by convection, according to the rule of Sections 3.3.5.2 - 3.3.5.4.

The "enthalpy of buoyancy" would tend to generate an upward- or downward-buoyant plume which would flow toward the ceiling or floor, respectively, of the receiving room. As such a plume impinged on the ceiling or floor surface, it would lead to a ceiling or floor jet. This would lead in turn to a convective heat transfer exchange between the gas and the surface. The heat transfer phenomena and losses for an upward-buoyant enthalpy of buoyancy is completely analogous to the heat transfer and losses for a fire plume. For a fire plume, the enthalpy convected upward from the fire's combustion zone, (1

$- \lambda_R)\dot{Q}$ [see Eq. (3.2.1)], is directly analogous to the enthalpy of buoyancy of the slab. Also, for an idealized fire with $\lambda_R = 0$, i.e., with negligible radiation loss, λ_V is completely analogous to λ_T [see Eq. (3.2.4)].

It is consistent with the guidance on the choice for λ_T in reference [2.1.4] to choose λ_V in the range $0.4 < \lambda_V < 0.8$. The default value for λ_V is taken to be 0.6 in CCFM.VENTS.

Following the above ideas, the net rate of heat transfer to the room surfaces is

$$\text{net rate of heat transfer to surfaces} = \lambda_V \cdot \dot{Q}_{SLAB} \cdot (1 - T_R/T_{PEN}) \tag{3.3.43}$$

and, the net rate of enthalpy flow deposited in the layers of the receiving room is

$$\begin{aligned}\text{net rate of enthalpy flow to layers} &= \dot{Q}_{SLAB} - \lambda_V \cdot \dot{Q}_{SLAB} \cdot (1 - T_R/T_{PEN}) \\ &= \dot{Q}_{SLAB} \cdot [1 - \lambda_V \cdot (1 - T_R/T_{PEN})]\end{aligned} \tag{3.3.44}$$

The rule for distributing the net rate of enthalpy flow of Eq. (3.3.44) between the two layers is taken to correspond to the earlier rule for distributing mass, oxygen, and products of combustion according to the fractions F_U and F_L determined in Section 3.3.5.2. Thus,

$$\text{rate of enthalpy flow to upper layer} = F_U \cdot \dot{Q}_{SLAB}[1 - \lambda_V \cdot (1 - T_R/T_{PEN})] \tag{3.3.45}$$

$$\text{rate of enthalpy flow to lower layer} = F_L \cdot \dot{Q}_{SLAB}[1 - \lambda_V \cdot (1 - T_R/T_{PEN})]$$

To the extent that an estimate of the actual distribution of heat transfer to surfaces is required, it is reasonable to assume that the net rate of heat transfer to room surfaces of Eq. (3.3.43) is distributed between surfaces engulfed by the upper and lower layers according to the values of F_U and F_L. Thus,

$$\text{rate of heat transfer to upper surfaces} = F_U \cdot \lambda_V \cdot \dot{Q}_{SLAB}(1 - T_R/T_{PEN})$$

(3.3.46)

$$\text{rate of heat transfer to lower surfaces} = F_L \cdot \lambda_V \cdot \dot{Q}_{SLAB}(1 - T_R/T_{PEN})$$

where, again, F_U and F_L are determined as in Section 3.3.5.2.

It is noteworthy that the above estimates lead to the result that the rates of heat transfer to surfaces will be positive or negative depending on whether T_{PEN} is greater or less than T_R, respectively. As illustrated in the two examples below, this is consistent with the assumption that in some semi-quantitative sense there is a correspondence between the characteristic surface temperature of the room and T_R.

In the first example, assume that $T_{PEN} > T_R$, i.e., $(1 - T_R/T_{PEN}) > 0$, and that the characteristic temperature of the upper surfaces of the receiving room is at the relatively-low-temperature, T_R (e.g., as in the situation of a room adjacent to a room of fire origin where the room-of-origin upper layer is just starting to be transferred through the upper part of an open doorway). Then the slab flow will lead typically to a relatively high-temperature upward-buoyant plume in the receiving room which will impinge on the relatively low-temperature ceiling. As predicted in Eqs. (3.3.45) and (3.3.46), this will lead to a positive rate of heat transfer to the ceiling (heating of the ceiling) and a corresponding negative component of rate of enthalpy addition to the plume/upper layer (cooling of the ceiling-impinging plume).

In the second example, assume that $T_{PEN} < T_R$, i.e., $(1 - T_R/T_{PEN}) < 0$, and that the characteristic temperature of the lower surfaces of the receiving room is at the relatively high-temperature, T_R (e.g., as in a scenario where relatively cool air from an adjacent space, the source of the flow slab, is introduced near the ceiling of the receiving room, which is also a room of fire origin). Then the slab flow will lead typically to a relatively low-temperature downward-buoyant plume which will impinge on the relatively high-temperature floor. As predicted in Eqs. (3.3.45) and (3.3.46), this will lead to a negative rate of heat transfer to the floor (cooling of the floor) and a corresponding positive component of rate of enthalpy addition to the plume/upper layer (heating of the floor-impinging plume).

3.3.5.6. Completing the Third Stage of the Calculation; Natural-Vent-Flow Calculations for the Total Facility

Contributions of any slab flow to the upper and lower layers of a pair of vent-connected rooms can be calculated by implementing the results and discussion of Sections 3.3.5.2 - 3.3.4.5. The contribution to the layers from an entire single vent flow is then obtained by carrying out sequentially the slab flow calculations for all of the one-to-six slab flows of the vent. This would complete the third stage of a vent-flow calculation.

The contribution to the layers from all vents in a single common-wall segment of a room pair is obtained by carrying out the vent calculations sequentially for all vents in the common-wall segment. This would involve both second- and third-stage types of calculations.

The contributions of natural vertical vent flows to the layers of all rooms of a facility is obtained by carrying out the common-wall segment vent calculations sequentially for all vent-containing common-wall segments of the facility. This would involve all three stages of the vent-flow calculations of Section 3.3.

It is important to note that when one of the two rooms in a calculation is the space associated with the outside environment, modifications to that outside space as a result of leaving or entering flow slabs are ignored.

3.3.6. The Algorithms and Associated Subroutines, COMWL1, DELP, VENTHP, and FLOGO2, Used to Carry Out the Three Stages of the Natural Vent Flow Calculation

The methodology described in Sections 3.3.1 - 3.3.5 for estimating the rates of exchange of mass, enthalpy, oxygen, and other products of combustion through vertical natural vents is implemented in four separate algorithms named DELP, COMWL1, VENTHP, and FLOGO2.

DELP, which is used by COMWL1 and VENTHP, is a utility-type of algorithm which implements the pressure calculations of Eqs. (3.3.2)-(3.3.5). COMWL1, VENTHP, and FLOGO2 implement the calculations of Stage 1, 2, and 3 and their corresponding Sections 3.3.3, 3.3.4, and 3.3.5, respectively. The use of these four algorithms is depicted in Figure 3.3.4.

A concise presentation of DELP, COMWL1, VENTHP, and FLOGO2 and their associated FORTRAN subroutine appears in Part III [1.1.2] of this work.

3.4. Forced Vent Flows and Heat Transfer - Two Options

This Section describes an algorithm for estimating the rates of flow of mass, enthalpy, oxygen, and other products of combustion through a well-insulated, forced-ventilation, fan/duct system connecting any two rooms, or a room and the outside environment in a multi-room facility. The rates of flow to and from the upper and lower layers of two connected spaces are determined explicitly. Figure 3.4.1 presents a sketch of the fire-generated environment in a pair of rooms connected by such a fan/duct system.

The terminology "well-insulated," used above to describe the fan/duct system, is meant to indicate that any heat transfer to the walls of the simulated fan/duct systems is assumed to be negligible.

The algorithm is implemented with one of two basic options. In Option 1, the direction of flow and the volume flow rate through the system is specified. In the more complicated option, Option 2, the instantaneous flow rate and direction of the flow are determined from specified fan characteristics, a specified duct resistance, and from the instantaneous characteristics of the two-layer room environment local to the end-points of the fan/duct system being simulated. In carrying out the calculation under Option 2, modeling of the fan/duct ventilation system follows an extension of the ideas presented in reference [3.4.1].

3.4.1. Two Stages of the Calculation

The forced-vent flow calculation is carried out in two stages.

In the first stage, the rates of extraction from the upper and lower layers of the source room are determined along with all the properties of the assumed-well-mixed the duct flow. When Option 2 is implemented and system characteristics are used to determine flow direction and net flow rate, an additional algorithm is used to perform the actual system-flow simulation. This algorithm is described below in Section 3.4.5.

The first-stage calculation concludes with a description of the flow from the source room into the duct, in the duct itself, and from the duct into the receiving room. The flows in and out of the duct are described in the manner of the VENTHP natural-vent flow slabs of Section 3.3.4. Here, there would be only one or two entry flow slabs and one or two exiting flow slabs depending on whether or not a smoke layer interface in the source or receiving room lies within the elevation limits of the fan/duct system vents in the respective rooms.

In the second-stage calculation, the distribution of the forced ventilation-driven flow slabs to the layers of the receiving room and their rate of extraction from the layers of the source room are determined with use of the algorithm FLOGO2 discussed in Section 3.3.5.

3.4.2. Specification of the Fan/Duct System Geometry and the Geometry and Fire Environment of the Connected Room Pairs

Identify the two rooms of the facility, or the room and the outside environment, connected by the fan/duct system and refer to the Figure 3.4.1. Number the rooms as room 1 or room 2 according to whether it is connected to the fan/duct system inlet or outlet, respectively. Here, the system inlet and outlet are defined as the side of the fan/duct flow system which corresponds to the flow inlet and outlet, respectively, under normal fan operating conditions. Normal operating conditions lead to what will be referred to here as flow in the normal or forward direction, from room 1 to room 2. Flow from outlet to inlet, i.e., from room 2 to room 1, will be referred to as backward flow. In the case of Option 1, where flow direction and flow rate are specified, the number identification of the rooms is arbitrary.

The elevation of the inlet and outlet end-point of the fan/duct system are characterized by the elevation of their midpoints, $y_{SYSTEM,i}$, in room i = 1 or 2, above a datum elevation. The vent openings at the duct end-points are assumed to be rectangular with sides aligned vertically and horizontally. H_i, the depth of these vents in room i, are also specified. These values are required in order to determine the effect on the fire environment of the system flow at instants of time when flow through the system is drawn partially from, or supplied partially to, both the upper and lower layer of room i.

The geometry of the two rooms and the state of the two-layer environment are specified as in Section 3.3.2. The required room geometry characteristics are the elevations above the datum elevation of the floors and ceilings, $y_{FLOOR,i}$ and $y_{CEIL,i}$, respectively.

The instantaneous states of the room environments are specified by the elevation of the interfaces, $y_{LAYER,i}$, separating the upper and lower layers and by the density, absolute temperature, mass concentration mass of O_2, and mass concentrations of the other (N_{PROD} - 1) products of combustion in the upper and lower layers of room i. The latter are designated by $\rho_{U,i}$ [$\rho_{L,i}$], $T_{U,i}$ [$T_{L,i}$], $c_{O2,U,i}$ [$c_{O2,L,i}$], and $c_{k,U,i}$ [$c_{k,L,i}$], k = 2 to N_{PROD}, respectively, for the upper [lower] layer. At instants of time when there is no upper layer [lower layer], i.e., when $y_{LAYER,i} = y_{CEIL,i}$ [$y_{LAYER,i} = y_{FLOOR,i}$], upper-layer [lower-layer] properties are not used in the calculation. Also, as in Sections 3.2 and 3.3, O_2 and other product concentrations would be required only when the simulation under consideration is actually being used to predict these concentrations.

The final specification of the environment is $\delta p_{FLOOR,i}$, the difference between the absolute hydrostatic pressure at the floor of each room and some fixed, absolute, hydrostatic datum pressure, p_{DATUM}.

Remarks at the end of Section 3.3.2, relative to situations where one of the "rooms" connected by a natural vent is the outside environment, are also applicable here. Also, as in Sections 3.2 and 3.3, all above-mentioned elevations are relative to the same datum elevation.

3.4.3. Specification of Fan/Duct System Characteristics

As mentioned above, there are two options for specifying the fan/duct system characteristics. In Option 1, the flow direction and volume flow rate through the system are specified. By electing to use this option, one assumes that during the course of a simulated fire scenario the rate of volumetric flow through the fan/duct system being modeled will not vary significantly from a specified design value, $\dot{V}_{DUCT}$. Both the direction and the magnitude of the volume flow rate are specified by the value of $\dot{V}_{DUCT}$. If $\dot{V}_{DUCT} > 0$ [$\dot{V}_{DUCT} < 0$] then the flow is forward [backward] flow from room 1 to room 2 [room 2 to room 1].

When using Option 2, the direction and magnitude of the flow rate through the fan/duct system are unknown. To carry out the required calculation these must be determined from specified fan/duct characteristics and knowledge of the above-mentioned parameters which define the two room environments.

When using Option 2, the specified fan/duct characteristics required are the fan curve and the duct's flow resistance.

The fan curve describes the operating characteristics of the fan. It is a plot of the cross-fan pressure difference, Δp_F, as a function of the fan volume flow rate, $\dot{V}_F$. Δp_F is defined as the difference between the pressures at the fan's outlet and the inlet sections. This is identical to the difference between $\delta p_{F,2}$, and $\delta p_{F,1}$, the outlet and inlet pressures, respectively, as measured relative to the datum pressure.

$$\Delta p_F = \delta p_{F,2} - \delta p_{F,1} \tag{3.4.1}$$

A generic fan curve is depicted in Figure 3.4.2.

The fan curve is defined analytically by linear interpolation between and linear extrapolation beyond two or more pairs of specified values, $[\dot{V}_{F,J}, \Delta p_{F,J}]$, J = 1 to JTERM > 1, which identify points on the curve. These points indicate the volume flow rate delivery of the fan, $\dot{V}_{F,J}$, at discrete cross-fan pressure differences, $\Delta p_{F,J}$.

In specifying the $[\dot{V}_{F,J}, \Delta p_{F,J}]$ data, the present model requires the $\Delta p_{F,J}$ to be monotonically decreasing with increasing $\dot{V}_{F,J}$. Points on the fan curve of Figure 3.4.2 would satisfy such a requirement.

The flow resistance through the duct would be dependent generally on flow direction. Designate the resistance as R_1 and R_2 for forward and backward flow, respectively. Also designate the density of the flow through the fan/duct system as ρ_{DUCT}. As will be determined below, this will also be dependent generally on flow direction. Then, given a non-zero pressure drop in the duct, Δp_{DUCT}, for a mass flow rate through the system duct, $\dot{M}_{DUCT}$, and corresponding volume flow rate, $\dot{V}_{DUCT}$, the non-zero resistances, R_i, are defined as

$$R_i = S_i |\Delta p_{DUCT}|^{1/2}/\dot{M}_{DUCT} = S_i |\Delta p_{DUCT}|^{1/2}/(\rho_{DUCT}\dot{V}_{DUCT})$$

$$\begin{aligned}\Delta p_{DUCT} &= (\delta p_{SYSTEM,1} - \delta p_{F,1}) + (\delta p_{F,2} - \delta p_{SYSTEM,2}) \\ &\quad + \rho_{DUCT} g(y_{SYSTEM,1} - y_{SYSTEM,2}) \\ &= \Delta p_F + (\delta p_{SYSTEM,1} - \delta p_{SYSTEM,2}) + \rho_{DUCT} g(y_{SYSTEM,1} - y_{SYSTEM,2})\end{aligned} \tag{3.4.2}$$

where, for forward flow, i = 1, $S_1 = 1$, and Δp_{DUCT} would be > 0, and for backward flow, i = 2, $S_2 = -1$, and Δp_{DUCT} would be < 0. Also, $\delta p_{SYSTEM,1}$ and $\delta p_{SYSTEM,2}$ are the pressures in rooms 1 and 2, relative to the datum pressure, at the elevations, $y_{SYSTEM,1}$ and $y_{SYSTEM,2}$, respectively, of the inlet and outlet system endpoints. Finally, consistent with the sketch of Figure 3.4.1, Eq. 3.4.2 assumes that there is a negligible difference in elevation between the inlet and outlet of the fan.

If the duct flow resistance is negligible, i.e., the duct resistances can be approximated by $R_1 = R_2 = 0$, then from the first of Eq. (3.4.2) Δp_{DUCT} would also be approximated as zero and from the second of Eq. (3.4.2) it follows that

if $R_1 = R_2 = 0$:

$$\Delta p_F = -(\delta p_{SYSTEM,1} - \delta p_{SYSTEM,2}) - \rho_{DUCT} g(y_{SYSTEM,1} - y_{SYSTEM,2}) \quad (3.4.3)$$

3.4.4. First Stage of the Calculation: Characteristics of the Flow Entering and Leaving the Duct

As noted in Section 3.4.3, for Option 2 a priori knowledge of the direction of the flow through a particular fan/duct system being simulated is unavailable. It can be from room 1 to room 2 or from room 2 to room 1. The latter possibility would indicate the backward flow condition where flow direction was opposite to that of normal fan operation. This must occur, for example, if there is a fire in room 2, the outlet room, and if all vents and other significant penetrations from room 2 are closed except for the room-2 end-point of the fan/duct system.

A priori knowledge of flow direction depends on which of the two above-mentioned algorithm options is implemented. To keep general the analysis in the discussion to follow, the subscripts i used in the variables identified in Section 3.4.2 are replaced by iFR, to denote the source room from which the duct flow is extracted, and by iTO, to denote the receiving room into which the duct flow is deposited. Then, one task of the first-stage calculation is to determine whether iFR = 1 and iTO = 2 (forward flow, or normal fan operation with $\dot{V}_{DUCT} > 0$) or iFR = 2 and iTO = 1 (backward flow through the fan, with $\dot{V}_{DUCT} < 0$).

3.4.4.1. Characterizing the Entering Duct Flow

Consider room iFR.

When the layer interface is not between the top and bottom of the duct opening a single uniform flow slab enters the duct with properties identical to the specified properties of the lower layer, if $y_{LAYER,iFR} \geq y_{SYSTEM,iFR} + H_{iFR}/2$; the upper layer, if $y_{LAYER,iFR} \leq y_{SYSTEM,iFR} - H_{iFR}/2$.

When the layer interface is between the top and bottom of the duct opening special considerations are required.

Figure 3.4.3 is an illustration of the flow entering the duct in room iFR when the layer interface is between the top and bottom of the vent opening. Define δp_{DUCT} as the pressure relative to the datum pressure at a location somewhat inside the duct, upstream of significant duct-flow development and mixing between the upper- and lower-layer flow contributions.

Assume that the flow through the vent and into the entry region of the duct is similar to the flow through an orifice or nozzle. Assume also that H_{iFR} is small enough so that the absolute value of the hydrostatic pressure difference over the height of the duct is negligible compared to the absolute value of the pressure drop, $|\Delta p_{ENTRY}| = |\delta p_{DUCT} - \delta p_{SYSTEM,iFR}|$, across the duct entrance region. Then, from Bernoulli's equation, e.g., Eq. (3.3.10) for $\bar{\epsilon} = 0$, the velocity of the upper and lower layer flow-slab components of the flow in the entrance region of the duct are both proportional to $|\Delta p_{ENTRY}|^{1/2}$. In particular, the mass flow rate of the two flow slabs from the upper and lower layer, $\dot{M}_{SLABU,iFR}$ and $\dot{M}_{SLABL,iFR}$, respectively, are given by

$$\dot{M}_{SLABU,iFR} = bC_D h_{U,iFR}(|\Delta p_{ENTRY}|\rho_{U,iFR})^{1/2}$$
$$\dot{M}_{SLABL,iFR} = bC_D h_{L,iFR}(|\Delta p_{ENTRY}|\rho_{L,iFR})^{1/2} \qquad (3.4.4)$$

In the above, b is the width of the vent and C_D is the flow coefficient. Also, as illustrated in Figure 3.4.3, $h_{U,i}$ $[h_{L,i}]$ is the absolute value of the difference in elevation in room i between the top [bottom] of the vent and the layer interface.

$$h_{U,i} = y_{SYSTEM,i} + H_i/2 - y_{LAYER,i}$$
$$h_{L,I} = H_i - h_{U,i} = y_{LAYER,i} - (y_{SYSTEM,i} - H_i/2) \qquad (3.4.5)$$

From Eq. (3.4.4) it follows that

$$\dot{M}_{SLABU,iFR}/\dot{M}_{SLABL,iFR} = (h_{U,iFR}/h_{L,iFR})(\rho_{U,iFR}/\rho_{L,iFR})^{1/2} \qquad (3.4.6)$$

Assume that once in the duct the two streams mix adiabatically to form a uniform-property duct flow of temperature T_{DUCT} and density ρ_{DUCT} where the upper- and lower-layer inlet flows can both be modeled as the same perfect gas, i.e.,

$$\rho_{DUCT}T_{DUCT} = \rho_{U,iFR}T_{U,iFR} = \rho_{L,iFR}T_{L,iFR} \qquad (3.4.7)$$

Adiabatic mixing requires that

$$\dot{M}_{SLABU,iFR}T_{U,iFR} + \dot{M}_{SLABL,iFR}T_{L,iFR} = |\dot{M}_{DUCT}|T_{DUCT}$$

$$= (\dot{M}_{SLABU,iFR} + \dot{M}_{SLABL,iFR})T_{DUCT} \quad (3.4.8)$$

Now Eqs. (3.4.6)-(3.4.8) lead to

$$\rho_{DUCT} = \rho_{DUCT,iFR} = \rho_{L,iFR}[1 + (h_{U,iFR}/h_{L,iFR})(\rho_{U,iFR}/\rho_{L,iFR})^{1/2}]/$$

$$[1 + (h_{U,iFR}/h_{L,iFR})(\rho_{L,iFR}/\rho_{U,iFR})^{1/2}] \quad (3.4.9)$$

Thus, if the flow direction (i.e., the value of iFR) is known, the above model for flow entry into the duct yields an estimate of $\rho_{DUCT,iFR}$ without specific knowledge of the value of $\dot{M}_{DUCT}$ or its entry flow-slab components, $\dot{M}_{SLABU,iFR}$ and $\dot{M}_{SLABL,iFR}$. Equation (3.4.9) will be used when the present forced-vent algorithm is implemented in the option-2 mode (see Section 3.4.5). At such times the values of ρ_{DUCT} under conditions of forward and backward flow through the ventilation system (i.e., for both possibilities, iFR = 1 or 2) are required to determine the direction and rate of flow through the fan/duct system.

Once the solutions to ρ_{DUCT} are determined by Eq. (3.4.9), Eq. (3.4.7) leads to T_{DUCT}

$$T_{DUCT} = \rho_{U,iFR}T_{U,iFR}/\rho_{DUCT} \quad (3.4.10)$$

Also, once the solution to $\dot{M}_{DUCT}$ is obtained from considerations in Section 3.4.4.3, Eqs. (3.4.6), (3.4.8), and (3.4.10) lead to $\dot{M}_{SLABU,iFR}$ and $\dot{M}_{SLABL,iFR}$

$$\dot{M}_{SLABL,iFR} = |\dot{M}_{DUCT}|T_{DUCT}/\{T_{U,iFR}[(h_{U,iFR}/h_{L,iFR})(\rho_{U,iFR}/\rho_{L,iFR})^{1/2}] + T_{L,iFR}\} \quad (3.4.11)$$

$$\dot{M}_{SLABU,iFR} = |\dot{M}_{DUCT}| - \dot{M}_{SLABL,iFR}$$

$$= |\dot{M}_{DUCT}|T_{DUCT}/\{T_{L,IFR}[(h_{L,IFR}/h_{U,IFR})(\rho_{L,IFR}/\rho_{U,IFR})^{1/2}] + T_{U,IFR}\} \quad (3.4.12)$$

3.4.4.2. **Determining the Entering Duct Flow When the Flow Direction and Flow Rate Are Specified**

When using Option 1, the values of $\dot{V}_{DUCT}$ and iFR are known, and the values of ρ_{DUCT}, T_{DUCT}, and $\dot{M}_{DUCT}$ and the entering components of the duct flow slabs are determined according to:

If the interface is between the top and bottom of the room-iFR vent:

There are two flow slabs entering the vent; ρ_{DUCT} and T_{DUCT} are determined from Eqs. (3.4.9) and (3.4.10), respectively; $\dot{M}_{DUCT} = \rho_{DUCT}\dot{V}_{DUCT}$; and, using the latter value for $\dot{M}_{DUCT}$, $\dot{M}_{SLABL,iFR}$ and $\dot{M}_{SLABU,iFR}$ are determined from Eqs. (3.4.11) and (3.4.12), respectively.

(3.4.13)

If the interface is at or below the bottom of the room-iFR vent:

There is one slab of flow entering the vent from the upper layer; $\rho_{DUCT} = \rho_{U,iFR}$; $T_{DUCT} = T_{U,iFR}$; $\dot{M}_{DUCT} = \rho_{DUCT}\dot{V}_{DUCT}$; $\dot{M}_{SLABU,iFR} = |\dot{M}_{DUCT}|$; and $\dot{M}_{SLABL,iFR} = 0$.

(3.4.14)

If the interface is at or above the top of the room-iFR vent:

There is one flow slab entering the vent from the lower layer; $\rho_{DUCT} = \rho_{L,iFR}$; $T_{DUCT} = T_{L,iFR}$; $\dot{M}_{DUCT} = \rho_{DUCT}\dot{V}_{DUCT}$; $\dot{M}_{SLABL,iFR} = |\dot{M}_{DUCT}|$; and $\dot{M}_{SLABU,iFR} = 0$.

(3.4.15)

From the above and from other specified information, all other properties of the entering flow slabs and the duct flow can also be determined.

3.4.4.3. **Determining the Entering Duct Flow When the Flow Rate and Flow Direction Are Unknown**

In the Option-2 mode, it is necessary to determine the entering flow slab components of the duct flow and the properties of the duct flow itself as in Option 1. Here, the system flow rate and the flow direction (i.e., the value of iFR) are not known.

To obtain the flow rate it is necessary first to determine

$$\Delta p_{SYSTEM} = \delta p_{SYSTEM,1} - \delta p_{SYSTEM,2} \quad (3.4.16)$$

where $\delta p_{SYSTEM,1}$ and $\delta p_{SYSTEM,2}$ are obtained from:

For i = 1 and 2:

If $y_{SYSTEM,i} > y_{LAYER,i}$:

$$\delta p_{SYSTEM,i} = \delta p_{FLOOR,i} - \rho_{L,i} g(y_{LAYER,i} - y_{FLOOR,i}) - \rho_{U,i} g(y_{SYSTEM,i} - y_{LAYER,i}) \quad (3.4.17)$$

If $y_{SYSTEM,i} \leq y_{LAYER,i}$:

$$\delta p_{SYSTEM,i} = \delta p_{FLOOR,i} - \rho_{L,i} g(y_{SYSTEM,i} - y_{FLOOR,i}) \quad (3.4.18)$$

Next, the two possible ρ_{DUCT} values, corresponding to forward and backward flow, are determined. These are designated as $\rho_{DUCT,1}$ if there is forward flow (i.e., if iFR = 1) and $\rho_{DUCT,2}$ if there is backward flow (i.e., if iFR = 2). The values of $\rho_{DUCT,i}$ are determined one at a time according to the Option-1 determination of ρ_{DUCT} presented in Eqs. (3.4.13)-(3.4.14).

Finally it is necessary to determine

$$\Delta y_{SYSTEM} = y_{SYSTEM,1} - y_{SYSTEM,2} \quad (3.4.19)$$

Now, with the values of Δp_{SYSTEM}, Δy_{SYSTEM}, the $\rho_{DUCT,i}$, and the characteristics of the fan-duct system, namely, the R_i, JTERM and the $[\dot{V}_{F,J}, \Delta p_{F,J}]$, J = 1 to JTERM, the algorithm described below (in Section 3.4.5) is used to determine $\dot{M}_{DUCT}$.
As will be mentioned in Section 3.4.5, there are situations where the adopted model of the fan-duct system can yield two solutions for the flow, a forward flow solution and a backward flow solution. Under such a circumstance, the solution adopted here is the one that corresponds to the flow direction determined at the previous time step in the fire simulation.

3.4.4.4. Characterizing the Flow as it Leaves the Fan-Duct System and Penetrates the Receiving Room

The first-stage calculation concludes with a characterization of the known, uniform-property duct flow as it leaves the fan/duct system and penetrates the layers of the receiving room, room iTO. In terms of a flow slab description of the penetrating flow, the following determination is made:

If the interface in room iTO is between the top and bottom of the room-iTO vent:

There are two, identical-property flow slabs leaving the vent. The upper flow slab consists of the portion of the duct flow between the elevation of the layer interface and the top of the vent, and the lower flow slab consists of that portion of the duct flow between the interface and the bottom of the vent. The upper and lower flow slabs have depths of $h_{U,iTO}$ and $h_{L,iTO}$ which are determined by Eq. (3.4.5), and they penetrate the upper and lower layers of room iTO, respectively. The mass flow rate in the upper and lower slabs are designated as $\dot{M}_{SLABU,iFR}$ and $\dot{M}_{SLABL,iFR}$, respectively. These are determined from

$$\dot{M}_{SLABU,iFR} = (h_{U,iTO}/H_{iTO})|\dot{M}_{DUCT}|$$

$$\dot{M}_{SLABL,iFR} = (h_{L,iTO}/H_{iTO})|\dot{M}_{DUCT}| = |\dot{M}_{DUCT}| - \dot{M}_{SLABU,iFR} \qquad (3.4.20)$$

If the interface in room iTO is at or below the bottom of the room-iTO vent:

There is one flow slab leaving the vent and penetrating the upper layer.

(3.4.21)

If the interface in room iTO is at or above the top of the room-iTO vent:

There is one flow slab leaving the vent and penetrating the lower layer.

(3.4.22)

The properties of the entering flow slabs are those of the duct flow.

3.4.5. The Direction and Flow Rate Through a Fan/Duct System

This Section describes the basis for calculating the flow rate through a fan/duct ventilation system of the type depicted in Figure 3.4.1. In carrying out the calculation, modeling of the system follows an extension to the ideas presented in reference [3.4.1].

In Figure 3.4.1, $y_{SYSTEM,1}$, $y_{SYSTEM,2}$ are the mid-elevation, relative to the datum elevation, of the system end-points in rooms 1 and 2, respectively. Also, $\delta p_{SYSTEM,1}$, $\delta p_{SYSTEM,2}$ are the pressures at these end-points, relative to the datum pressure. As defined in Section 3.4.2 and as indicated in the figure, the end-points 1 and 2 correspond to the inlet and outlet of the system under normal fan operating conditions.

To carry out the present calculation, several parameters of the system must be specified. These are: the pressure and elevation differences, Δp_{SYSTEM} and Δy_{SYSTEM}, as defined in Eqs. (3.4.16) and (3.4.19); the forward and backward flow resistance of the duct, R_1 and R_2, respectively, as defined in Eq. (3.4.2); and the two possible densities of the duct flow, designated as $\rho_{DUCT,1}$, if the solution flow is a forward flow from the inlet room 1 to the outlet room 2, and $\rho_{DUCT,2}$, if the solution flow is a backward flow from the outlet room 2 to the inlet room 1.

Also required for the calculation are two or more pairs of specified values $[\dot{V}_{F,J}, \Delta p_{F,J}]$, J = 1 to JTERM > 1, which identify points on the fan-operating curve. As defined in Section 3.4.3, the $\dot{V}_{F,J}$'s are the volume flow rates delivered by the fan under the corresponding cross-fan pressure differences $\Delta p_{F,J}$, where Δp_F is defined in Eq. (3.4.1). As indicated in Section 3.4.3, in simulating fan operation the fan curve is approximated by linear interpolation between and linear extrapolation beyond the specified JTERM fan-curve data points. As indicated in Figure 3.4.2, the fan curve must be such that Δp_F is monotonically decreasing with increasing $\dot{V}_F$. In terms of the fan curve, forward flow is associated with positive values of the volume flow rate, $\dot{V}_F$, while backward flow is associated with negative values of $\dot{V}_F$.

Let the simulated fan curve be defined as

$$\dot{V}_F = f(\Delta p_F) \qquad (3.4.23)$$

and define its $\dot{V}_F = 0$ intercept as $\Delta p_{F,0}$, i.e.,

$$f(\Delta p_{F,0}) = 0 \qquad (3.4.24)$$

Also, using the above-specified parameters and referring to Eqs. (3.4.2), (3.4.16), and (3.4.19), define and evaluate the adjusted pressure differences, $\Delta p_{ADJ,i}$, as

$$\Delta p_{ADJ,i} = \Delta p_{SYSTEM} + \rho_{DUCT,i} g \Delta y_{SYSTEM} \quad (3.4.25)$$

where i = 1 or 2 for forward or backward flow, respectively.

Using Eq. (3.4.25) in Eq. (3.4.2) leads to the following result for the duct mass and volume flow rates:

$$\dot{M}_{DUCT,1} = \rho_{DUCT,1}\dot{V}_{DUCT,1} = |\Delta p_F + \Delta p_{ADJ,1}|^{1/2}/R_1 \text{ if } (\Delta p_F + \Delta p_{ADJ,1}) > 0 \quad (3.4.26)$$

$$\dot{M}_{DUCT,2} = \rho_{DUCT,2}\dot{V}_{DUCT,2} = -|\Delta p_F + \Delta p_{ADJ,2}|^{1/2}/R_2 \text{ if } (\Delta p_F + \Delta p_{ADJ,2}) < 0 \quad (3.4.27)$$

For a valid fan/duct system flow solution, the duct volume flow rate in Eqs. (3.4.26) or (3.4.27) and its corresponding mass flow rate must be identical to the fan volume flow rate of Eq. (3.4.23) and its corresponding mass flow rate. Equating these volume flow rates leads to the following result:

For non-zero R_i, Δp_F solutions to

$$|\Delta p_F + \Delta p_{ADJ,1}|^{1/2}/(\rho_{DUCT,1}R_1) = f(\Delta p_F) \text{ if } f(\Delta p_F) \geq 0$$

or (3.4.28)

$$-|\Delta p_F + \Delta p_{ADJ,2}|^{1/2}/(\rho_{DUCT,2}R_2) = f(\Delta p_F) \text{ if } f(\Delta p_F) \leq 0$$

and the corresponding $\dot{V}_{DUCT} = \dot{V}_F$ solutions that would be obtained from Eq. (3.4.23), would represent valid $[\dot{V}_F, \Delta p_F]$ solution pairs to the desired fan/duct flow problem.

If the duct flow resistance is negligible then Eqs. (3.4.3) and (3.4.25) lead to the following alternative to the result of Eq. (3.4.28):

For $R_1 = R_2 = 0$, the Δp_F solutions

$$\Delta p_F = -\Delta p_{ADJ,1} \text{ if } f(-\Delta p_{ADJ,1}) > 0$$

$$\text{or} \qquad (3.4.29)$$

$$\Delta p_F = -\Delta p_{ADJ,2} \text{ if } f(-\Delta p_{ADJ,2}) > 0$$

and the corresponding $\dot{V}_{DUCT} = \dot{V}_F$ solutions that would be obtained from Eq. (3.4.23) would represent valid $[\dot{V}_F, \Delta p_F]$ solution pairs to the desired fan/duct flow problem.

If Eqs. (3.4.28) or (3.4.29) do not lead to any solutions, then the solution to the duct/fan flow problem is one of zero flow, i.e.,

$$\dot{V}_{DUCT} = \dot{V}_F = 0 \text{ and } \Delta p_F = \Delta p_{F,0} \quad \text{if there are no solutions to Eqs. (3.4.28) or (3.4.29).} \qquad (3.4.30)$$

Figure 3.4.4 is a graphical presentation of the problem of solving Eqs. (3.4.28) or (3.4.29). Plotted there is the universal fan curve of Eq. (3.4.23), the solid line, and in the dashed lines, parametric plots of Eq. (3.4.26) for forward duct flow on the right side of the Δp axis, and parametric plots of Eq. (3.4.27) for backward duct flow on the left side of the Δp axis.

The parametric curves on the right side of Figure 3.3.4 characterize forward flow through the duct. According to Eq. (3.4.26), these correspond to plots of Δp_F vs $\dot{V}$ for different values of $\Delta p_{ADJ,1} = \sigma_1^{(F)}$, $\sigma_2^{(F)}$, $\sigma_3^{(F)} = 0$, $\sigma_4^{(F)}$, etc. At any instant and for any duct design, the value of $\Delta p_{ADJ,1}$ calculated from Eq. (3.4.25) would be equal to one of these $\sigma^{(F)}$ values (or to an interpolated value). Then the plot of Δp_F vs $\dot{V}$ for the duct would be identical to the corresponding $\sigma^{(F)}$ curve shown in the figure (or to an interpolated curve between the ones shown).

In an analogous way, the parametric curves on the left side of Figure 3.3.4 characterize backward flow through the duct. According to Eq. (3.4.27), these correspond to plots of Δp_F vs $\dot{V}$ for different values of $\Delta p_{ADJ,2} = \sigma_1^{(B)}$, $\sigma_2^{(B)}$, $\sigma_3^{(B)}$, $\sigma_4^{(B)} = 0$, etc. At any instant and for any duct design, the value of $\Delta p_{ADJ,2}$ calculated from Eq. (3.4.25) would be equal to one of these $\sigma^{(B)}$ values (or to an interpolated value). Then the plot of Δp_F vs $\dot{V}$ for the duct would be identical to the corresponding $\sigma^{(B)}$ curve shown in the figure (or to an interpolated curve between the ones shown).

Note that if duct flow resistance is zero, then from Eq. (3.4.29) the parametric duct-flow curves become the parametric horizontal lines

$$\dot{V}_{DUCT} > 0 \text{ and } \Delta p_F = -\Delta p_{ADJ,1} \text{ if } R_1 = 0 \qquad (3.4.31)$$

for forward flow, and

$$\dot{V}_{DUCT} < 0 \text{ and } \Delta p_F = -\Delta p_{ADJ,2} \text{ if } R_2 = 0 \qquad (3.4.32)$$

for backward flow.

In Figure 3.4.4, a valid forward-flow solution would correspond to the unique intersection of the solid fan curve and the dashed duct curve on the right which corresponds to the particular value of $\sigma^{(F)} = \Delta p_{ADJ,1}$ calculated in Eq. (3.4.25). In the figure it can be seen from the intercepts of the $\sigma_N^{(F)}$ curves and the Δp_F axis that a forward-flow solution, $\Delta p_{F,SOLN}$, exists if and only if $\Delta p_{FDJ,1}$ satisfies $-\sigma^{(F)} = -\Delta p_{ADJ,1} < \Delta p_{F,0}$.

Analogous to the forward flow solution, a valid backward-flow solution would correspond to the unique intersection of the solid fan curve and the dashed duct curve on the left which corresponds to the particular value of $\sigma^{(B)} = \Delta p_{ADJ,2}$ calculated in Eq. (3.4.25). In the figure it can be seen from the intercepts of the $\sigma_N^{(B)}$ curves and the Δp_F axis that a backward-flow solution, $\Delta p_{F,SOLN}$, exists if and only if $\Delta p_{ADJ,2}$ satisfies $-\sigma^{(B)} = -\Delta p_{FDJ,2} > \Delta p_{F,0}$.

The graphical presentation of Figure 3.4.4 clarifies the fact that there are four possible classes of solution to Eqs. (3.4.28) or (3.4.29), namely: a single forward-flow solution and no backward-flow solution, e.g., $\Delta p_{ADJ,1} = \sigma_2^{(F)}$ and $\Delta p_{ADJ,2} = \sigma_3^{(B)}$ [see Figure (3.4.5.a)], a single backward-flow solution and no forward-flow solution, e.g., $\Delta p_{ADJ,1} = \sigma_1^{(F)}$ and $\Delta p_{ADJ,2} = \sigma_1^{(B)}$ [see Figure (3.4.5.b)], one forward-flow solution and one backward-flow solution, e.g., $\Delta p_{ADJ,1} = \sigma_2^{(F)}$ and $\Delta p_{ADJ,2} = \sigma_1^{(B)}$ [see Figure (3.4.5.c)], and no solutions at all, e.g., $\Delta p_{ADJ,1} = \sigma_1^{(F)}$ and $\Delta p_{ADJ,2} = \sigma_2^{(B)}$ [see Figure (3.4.5.d)]. In the first two classes, the unique solution obtained is taken to be the desired solution to the fan/duct flow problem. In the latter class, the solution to the fan/duct flow problem is taken to be that of Eq. (3.4.30). As mentioned at the end of Section 3.4.4.3, when both forward- and backward-flow solutions are obtained (i.e., the third class of solution) the solution to the fan/duct flow problem is taken to be the solution with a flow direction identical to the flow direction determined at the previous instant of time in the fire simulation.

The actual solution to Eq. (3.4.28) makes use of the root-finding algorithm RTSAFE and its associated subroutine presented in [3.4.2]. The RTSAFE subroutine is a part of the FANRES subroutine of CCFM.VENTS which is included in Part III [1.1.2] of this work.

3.4.6. Second Stage of the Calculation: Distribution of the Duct Flow Slabs to the Receiving Layers and Rate of Extraction From the Source Layers

The result of the first-stage calculation of Section 3.4.4 is a description of the flows in and out of the fan/duct system where these flows are described in the manner of the VENTHP natural vent flow slabs of Section 3.3.4. In the second-stage calculation, the distribution of the present forced ventilation-driven flow slabs to the layers of the receiving room and their rate of extraction from the layers of the source room are determined according to the algorithm FLOGO2 discussed in Section 3.3.5.

As will be recalled, FLOGO2 provides the contributions to the rates of change of the upper and lower layers of two immediately adjacent rooms as a result of the one-to-six slabs of uniform-property flow which pass through a vertical vent in their common wall segment.

In the configuration of Figure 3.4.1, the flow slabs associated with the vent flows at either end of the fan/duct system have been determined; the flow from the source room to the duct, at one end, and the flow from the duct to the receiving room, at the other. Two successive applications of the FLOGO2 algorithm are used. In the first application, the pair of immediately adjacent rooms identified in the algorithm is the source room, room iFR, and a "dummy room," associated with the outside environment. The latter is taken as a surrogate for the FLOGO2 receiving room. In the second application, the pair of adjacent rooms is the receiving room, room iTO, and a "dummy room," now taken as a surrogate to the FLOGO2 source room. As mentioned at the end of Section 3.3.5.6, when one of the rooms of a room pair in a FLOGO2 calculation is a space associated with the outside environment, modifications to that outside space as a result of leaving or entering flow slabs are ignored. Therefore, in determining the action of the forced ventilation system the result of the two applications of FLOGO2 are 1) to calculate the rates of loss of mass, enthalpy, and products from the layers of the source room; and 2) to calculate the rates of addition of mass, enthalpy and products to the layers of the receiving room.

The contributions of forced ventilation flows to the layers of all rooms of a facility is obtained by carrying out the above fan/duct calculations sequentially for all fan/duct systems of the facility. For each system this would involve both stages of the calculations of Section 3.4.

3.4.7. The Algorithms and Associated Subroutines, VENTF, FLOGO2, and FANRES, Used to Carry Out the Two Stages of the Forced Vent Flow Calculation

The methodology described in Sections 3.4.1 - 3.4.6 for estimating the rates of exchange of mass, enthalpy, and products of combustion through forced-ventilation fan/duct systems is implemented in three separate algorithms named VENTF, FANRES, and FLOGO2.
VENTF implements the calculations of Stage 1 which correspond to the presentation in Section 3.4.4. FLOGO2 implements the calculations of Stage 2 which correspond to the presentation in Sections 3.4.6 and 3.3.5. In cases where the flow through the fan/duct system is determined from the duct flow

resistance and the fan operating curve, the algorithm FANRES is used in the VENTF calculation. The calculation of FANRES corresponds to the presentation in Section 3.4.5.

The use of the three algorithms of the forced vent calculation is depicted in Figure 3.4.6.

A concise presentation of VENTF, FANRES, and FLOGO2 and their associated FORTRAN subroutines appears in Part III [1.1.2] of this work.

4. Specifying the Problem for a Particular CCFM.VENTS Fire Simulation

To carry out a particular fire simulation with CCFM.VENTS the user must supply information on the characteristics of the rooms, the natural vents, the forced vents, the fires, and the outside environment. Also required are the initial conditions which describe the state of the two-layer environment in each room of the simulated facility. The required inputs will be discussed here briefly Other required inputs, not associated with the physical aspects of the simulation, will be discussed in Part II [1.1.1] of this work.

The detailed mechanics of implementing all CCFM.VENTS input are described in user's reference guide of Part IV [1.1.3].

4.1. Room Geometry, Vent Characteristics, and the Outside Environment

Independent sets of positive integers are used to number and designate the inside rooms, the natural vents, and the forced vents (i.e., the fan/vent systems) of the facility.

As will be discussed below, when dealing with wind environments and for other applications, it will be useful to divide conceptually the outside environment into a number of different spaces. These outside spaces would also be given designations from an independent set of positive numbers. When identifying one of these outside spaces, e.g., to specify that it is one of the two spaces joined by a vent, the assigned integer for the outside space is distinguished from that of the inside room by use of the negative of its designated integer value. In what is likely to be the most typical of fire scenarios, when the outside environment is taken to be quiescent and uniform, only one outside space is required. This space is designated as outside-environment space 1.

The specified geometric properties of each room i are $y_{FLOOR,i}$ and its height and area.

The specified properties of each natural vent i are: the numerical designation of the two inside rooms (or the inside room and outside space) connected by the vent, one of these being identified arbitrarily as the "from" room and the other as the "to" room; the area of the vent; and the elevations, above the floor of the "from" room, of the bottom and top of the vent.

The specified properties of each forced vent i are: the numerical designation of the "from" room and the "to" room under normal fan-operating conditions; the elevations above the floors of their respective rooms of the midpoints of the fan/duct system endpoints; the heights of the rectangular duct end-point vents in the "from" and in the "to" rooms; the flow resistances of the duct during forward and backward flow conditions; and a set of pairs of values of volume flow rate and cross-fan pressure which identify points on the fan curve.

The specified properties of each outside space i are: a reference elevation, relative to the datum elevation, where ambient properties of the space are specified; the reference pressure, relative to the datum pressure, at the latter elevation; the density of the space; and the concentration in the space of all simulated products of combustion.

4.2. The Fire

The specified properties of the fires are: the numbers of the rooms that contains a fire; the elevation of the fire above the floor; and sets of pairs of values of energy release-rate and time which identify points on the specified curves of fire-energy-release-rates vs time. In the simulation, for each of the specified fires the fire-energy-release-rate at an arbitrary time is obtained by interpolating linearly between or extrapolating linearly beyond the specified data points.

4.3. The Products of Combustion

An independent set of positive integers is used to number and designate the different products of combustion whose concentration is to be simulated. At an arbitrary instant of time it is assumed that the fire's generation rate of product of combustion k, $\dot{P}_{k,SOURCE}$, is proportional to the simulated energy-release-rate of the fire, i.e.,

$$\dot{P}_{k,SOURCE} = factor_k \cdot \dot{Q} \tag{4.3.1}$$

Thus, for product k, the specified property of the product generation rate is the constant, $factor_k$. The default product of combustion 1 is oxygen and, according to Eqs. (3.2.2), (3.2.3), and (4.3.1), a default value for $factor_1$ is specified as $-0.076(10^{-6})$(kg of O_2)/J.

4.4. Initial Conditions

The environment in each room i of the facility must be initialized. The initial properties specified are: $\delta p_{FLOOR,i}$, elevation of the layer interface above the floor, $\rho_{U,i}$, $\rho_{L,i}$, and $P_{k,U,i}$ and $P_{k,L,i}$ for each product of combustion, k. Note that if the upper layer is initially of zero thickness, then $\rho_{U,i}$ and the $P_{k,U,i}$ can be specified arbitrarily. Similarly, if the upper layer initially fills the room, $\rho_{L,i}$ and the $P_{k,L,i}$ can be specified arbitrarily.

As will be seen in Part IV [1.1.3], a simple procedure, appropriate for use in most simulations, is available for initializing all of the above variables. In this procedure: 1) all rooms of the facility are initialized with a zero-thickness upper-layer; and 2) the density and concentration of each product of combustion are taken to be uniform, at specified values, throughout all rooms of the facility and throughout all outside spaces. With the above specified information, the exact values of $\delta p_{FLOOR,i}$ for all rooms is calculated automatically. The procedure leads to the desired condition of initial-zero-flow between all inside-to-inside and inside-to-outside natural vents of the facility.

Having used the above initialization procedure, the user, as required, can then make initialization modifications to the outside spaces and to selected inside rooms.

4.5. Specifying a Simulation Which Accounts for Conditions of Wind Loading

Except in unusual situations where it is reasonable to model a facility as being completely sealed off from the outside environment, outside wind conditions can play a significant role in determining the fire-generated environment within the facility. This is because: 1) the wind dynamics affect significantly the exterior pressure distribution local to the outside-environment-exposed side of any particular natural or forced vent; and 2) such an exterior pressure distribution plays a major role in determining the characteristics of the flow through the vent, e.g., this distribution would be computed and used in the algorithm VENTHP.

The free-field wind velocity relative to the orientation of the facility and the specific location on the exterior of the facility structure will determine the local pressure distribution there. The location and shape of nearby structures can also play a role in determining the exterior pressure distribution.

The CCFM.VENTS capability of designating multiple outside spaces can be used to simulate the pressure distributions at different vent locations on the exterior of a facility in a wind environment. One possible method of using CCFM.VENTS to simulate such wind conditions is outlined briefly:

Specify ρ_{AMB}, the density of a quiescent environment, δp_{REF}, its reference pressure at its reference elevation, and y_{REF}, its reference elevation. Designate this environment as outside space 1.

Now assume that the environment is not quiescent, but that it has a uniform far-field wind velocity with wind speed, v_{WIND}.

Consider a vent of a facility which is exposed to an outside wind environment. Assume that an analysis of wind flow around the facility allows one to determine the local pressure coefficient, $C_{PRESSURE}$, at the location of the exposed-side of the vent of interest (see, e.g., [4.5.1]). Thus, if $\delta p_{QUIESCENT}$ and δp_{WIND} are the relative outside pressures local to the vent in the quiescent and wind environments, respectively, then, by definition of $C_{PRESSURE}$,

$$\delta p_{WIND} = \delta p_{QUIESCENT} + C_{PRESSURE}(\rho_{AMB} v_{WIND}^2/2) \qquad (4.5.1)$$

In view of Eq. (4.5.1), a new outside space is introduced, where the new space is defined as having the same properties as the original quiescent-environment space, but with a new reference pressure specified to be

$$\delta p_{REFNEW} = \delta p_{REF} + C_{PRESSURE}(\rho_{AMB} v_{WIND}^2/2) \qquad (4.5.2)$$

The "room" on the exposed side of the vent of interest is now designated as this new outside space.

Now the above procedure is repeated for each exposed vent of the facility. At the end of the process one outside space will be defined for each unique value of $C_{PRESSURE}$.

With the modified input data, the desired effect of wind loading would be taken account of in the resulting CCFM.VENTS simulation.

4.6. Stack Effect

Flows through natural vents located on the exterior walls of the facility (e.g., cracks, open windows, or doors) can be driven by cross-vent pressure differences which are set up as a result of a density difference between the interior of a facility and the outside environment. The flow exchange phenomenon is called stack effect [4.6.1].

The phenomenon of stack effect can be very important in relatively tall buildings during winter or summer conditions. The winter condition involves a relatively-uniform interior-building environment which has a lower density (higher temperature) than the density (temperature) of the outside ambient. The summer stack-effect phenomenon involves a relatively high interior density (low interior temperature) and relatively low outside ambient density (high outside temperature).

The combined phenomena of stack-effect-driven flows and fire-driven flows can be simulated with CCFM.VENTS. One possible way to do this is outlined briefly:

Initialize the simulation according to Section 4.4, setting the uniform inside and outside density at identical values corresponding to the desired inside density. Now modify the outside environment by specifying the desired outside density.

With the modified input data, the CCFM.VENTS simulation will include the desired phenomenon of stack effect.

Note that the ideas on wind-load simulation of Section 4.5 can be combined with the present ideas on stack-effect simulation. This leads to a capability of simulating the combined effect of fire, wind, and stack effect.

5. Summary and Overview of Parts II-IV

This is the first of a four-part report which documents all aspects of CCFM.VENTS, the first-stage prototype application of the CCFM concept. Introductory remarks of Section 1 discussed the generic features of the CCFM, and the specific features of CCFM.VENTS.

The main objective of this Part I document was to present a comprehensive description of the governing equations or algorithms used in CCFM.VENTS and their technical basis. This was done in Sections 2, where the generic CCFM equation set was presented and in Section 3 where the detailed technical basis of the CCFM.VENTS-specific equations were presented. Section 4 presented an overview of the task of specifying a particular CCFM.VENTS simulation. Methods of using CCFM.VENTS to simulate the phenomena of wind loading and stack effect were also discussed in this section.

The other three parts of this CCFM.VENTS documentation are: Part II: Software Reference Guide [1.1.1]; Part III: Catalog of Algorithms and Subroutines [1.1.2]; and Part IV: User Reference Guide [1.1.3].

Part II presents the generic and CCFM.VENTS-specific features of the framework of CCFM software. This includes features of both program and data structures. Numerical considerations used to treat the solution to the CCFM equation set are also presented. Part II concludes with a presentation of methods of using the CCFM structure to generate stages of the computer model beyond CCFM.VENTS.

Part III is a catalog of all the modular algorithms and associated computer subroutines used to simulate the physical phenomena in CCFM.VENTS. The catalog has two kinds of entries, algorithms which involve physical phenomena and other "utility" algorithms required in the physical algorithm calculations. Each physical algorithm entry of the catalog includes a brief description of the phenomenon simulated, a concise but complete presentation of the calculation procedure used, identification of all input and output parameters, and a listing of the computer coding. These catalog entries represent the bridge between the governing equations of CCFM.VENTS and their technical basis, as presented in Section 3 of this report, and the implementation of these mathematical modeling results into the software of CCFM, or of any other modular, zone-type, compartment fire model computer code.

Part IV is the CCFM.VENTS user's guide.

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NOMENCLATURE

A	a constant, Eq. (3.3.24)
B	a constant, Eq. (3.3.24)
b	width of a vent
C	vent flow coefficient, Eq. (3.3.14)
$\tilde{C}$	C at $\tilde{y}$
C_D	flow coefficient for entering duct flow
$C_{INCOMPRESSIBLE}$	C for incompressible flow
$C_{PRESSURE}$	local pressure coefficient
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
$c_{k,PEN}$	concentration of product of combustion k in a flow slab as it penetrates the receiving room
$c_{k,U}$ [$c_{k,L}$]	concentration of product of combustion k per unit mass of upper [lower] layer of a room
$c_{k,U,i}$ [$c_{k,L,i}$]	concentration of product of combustion k per unit mass of upper [lower] layer of room i
$c_{k,1}$ [$c_{k,2}$]	concentration of product of combustion k in room 1 [room 2] at the elevation of a vent flow slab
$c_{O2,U}$ [$c_{O2,L}$]	concentration of O_2 per unit mass of upper [lower] layer of a room
$c_{O2,U,i}$ [$c_{O2,L,i}$]	concentration of O_2 per unit mass of upper [lower] layer of room i
$c_{O2,1}$ [$c_{O2,2}$]	concentration of O_2 in room 1 [2] at the elevation of a vent flow slab
$c_{O2,PEN}$	concentration of O_2 in a flow slab as it penetrates the receiving room
F	a constant, Eq. (3.2.3)
F_U [F_L]	fraction of flow slab deposited into upper [lower] layer of receiving room

f	vent flow function, Eq. (3.3.13), or fan curve function, Eq. (3.4.23)
$factor_k$	multiplying factors to predict $\dot{P}_{k,SOURCE}$ from $\dot{Q}$, Eq. (4.3.1)
g	acceleration of gravity
H_i	depth of vents at the endpoints of a fan/duct system in room i
$h_{U,i}$ $[h_{L,i}]$	magnitude of the difference in elevation in room i between the top [bottom] of the vent and the layer interface
I_{DIR}	indicator of flow direction of a vent flow slab
JTERM	number of points used to approximate the fan curve >
$M_{U,i}$ $[M_{L,i}]$	mass in upper [lower] layer of room i
$\dot{M}_{PLUME}$	mass flow rate in the plume as it penetrates the layer interface
$\dot{M}_{DUCT}$	mass flow rate through the duct
$\dot{M}_{DUCT,1}$ $[\dot{M}_{DUCT,2}]$	mass flow rate through fan/duct system if its source is room 1 [room 2]
$\dot{M}_{SLAB}$	mass flow rate in a flow slab
$\dot{M}_{SLABU,iFR}$ $[\dot{M}_{SLABL,iFR}]$	mass flow rate in a flow slab entering a fan/duct system from the upper [lower] layer of room iFR
$\dot{M}_{U,i}$ $[\dot{M}_{L,i}]$	sum of mass flow rate contributions to the upper [lower] layer of room i from all plumes, jets, sources, etc.
$\dot{M}_U$ $[\dot{M}_L]$	a mass flow rate to the upper [lower] layer
N_{PROD}	number of products of combustion in the simulation
N_{ROOM}	number of rooms in the simulation
N_{SLAB}	number of flow slabs through a vent
N_{VELEV}	number of unique elevations of the endpoints and zeros of linear segments of a $\Delta p_{1,2}$ distribution along entire height of a vent

N_{WELEV}	number of unique elevations of the endpoints and zeros of linear segments of a $\Delta p_{1,2}$ distribution along entire length of a common wall segment
$P_{k,U,i}$ $[P_{k,L,i}]$	amount of product of combustion k in upper [lower] layer of room i
$\dot{P}_{k,SLAB}$	flow rate of product of combustion k in a flow slab
$\dot{P}_{k,SOURCE}$	fire generation rate of product of combustion k
$\dot{P}_{k,U,i}$ $[\dot{P}_{k,L,i}]$	sum of product of combustion k flow rate contributions to the upper [lower] layer of room i from all plumes, jets, sources, etc.
$\dot{P}_{k,U}$ $[\dot{P}_{k,L}]$	a product k flow rate to the upper [lower] layer
$\dot{P}_{O2,SLAB}$	O_2 flow rate in a flow slab
$\dot{P}_{O2,SOURCE}$	rate of O_2 generated by the fire
p	absolute pressure
p_{DATUM}	absolute datum pressure
p_N	p at y_N
p_i	absolute pressure in room i
$p_{FLOOR,i}$	p at elevation yFLOOR,i in room i
Q^*	dimensionless $\dot{Q}_{SOURCE}$, Eq. (3.2.7)
$\dot{Q}$	total energy-release rate of the fire
$\dot{Q}_{SLAB}$	enthalpy flow rate in a flow slab
$\dot{Q}_{SOURCE}$	$(1 - \lambda_R)\dot{Q}$
$\dot{Q}_{TOTAL}$	$(1 - \lambda_T)\dot{Q}$
$\dot{Q}_{U,i}$ $[\dot{Q}_{L,i}]$	sum of enthalpy plus heat transfer plus energy release flow rates to the upper [lower] layer of room i from all plumes, jets, sources etc.
$\dot{Q}_U$ $[\dot{Q}_L]$	a flow rate of enthalpy, heat transfer, and/or energy release to the upper [lower] layer of a room
R	gas constant
R_1 $[R_2]$	duct flow resistance for forward [backward] flow

S_i	indicator of flow direction, Eq. (3.4.2)
T_{DUCT}	absolute temperature of flow in the duct
T_{PEN}	absolute temperature of a flow slab as it penetrates the receiving room
T_{PLUME}	average temperature of fire plume gases at layer interface
T_R	absolute temperature of the layer in the receiving room which includes the elevation y_{SLAB}
T_U [T_L]	absolute temperature of upper [lower] layer in a room
$T_{U,i}$ [$T_{L,i}$]	absolute temperature of upper [lower] layer in room i
T_1 [T_2]	absolute temperature in room 1 [room 2] at the elevation of a vent flow slab
V_i	volume of the room i
$V_{U,i}$	volume of upper layer in room i
$\dot{V}_{DUCT}$	volume flow rate through a fan/duct system
$\dot{V}_{DUCT,1}$ [$\dot{V}_{DUCT,2}$]	volume flow rate through fan/duct system if its source is room 1 [room 2]
$\dot{V}_F$	volume flow rate through the fan
$\dot{V}_{F,J}$	volume flow rate corresponding to point J on the fan curve
v	velocity in a flow slab as it enters receiving room
v_{WIND}	wind speed
w	Eq. (3.3.12)
$\bar{w}$	w at $\bar{y}$
x	$1 - \epsilon$
$\bar{x}$	x at $\bar{y}$
y	arbitrary elevation within a room of interest above datum elevation
$\hat{y}$	is an arbitrary fixed value of y within a room
$\bar{y}$	mid-elevation of flow slab

y_{CEIL}	elevation of ceiling of a room above datum elevation
$y_{CEIL,i}$	elevation of ceiling of room i above datum elevation
y_{FIRE}	elevation of fire above datum elevation
y_{FLOOR}	elevation of floor of a room above datum elevation
$y_{FLOOR,i}$	elevation of floor of room i above datum elevation
y_{LAYER}	elevation of layer interface of a room above datum elevation
$y_{LAYER,i}$	elevation of layer interface of room i above datum elevation
y_{MIN} [y_{MAX}]	minimum [maximum] bounds for y of a vertical vent between two adjacent rooms, Eq. (3.3.5)
y_N	elevation N, above the datum elevation, where a $\Delta p_{1,2}$ distribution has an endpoint or a zero
y_{REF}	reference elevation above datum elevation
y_{SLAB}	characteristic elevation of a flow slab
$y_{SYSTEM,i}$	elevation above datum elevation of the midpoints of the inlet and outlet end-points of the fan/duct system in room i
y_{VTOP} [y_{VBOT}]	elevation, above a datum elevation, of top [bottom] of a vent
Z	elevation of layer interface above fire
y_{VTOP} [y_{VBOT}]	elevation, above a datum elevation, of top [bottom] of a vent
γ	C_p/C_v
Δp	$\Delta p_{1,2}$
$\Delta p_{ADJ,1}$ [$\Delta p_{ADJ,2}$]	adjusted pressure difference for fan/duct flow from room 1 [room 2], Eq. (3.4.25)
Δp_{DUCT}	pressure drop across the duct, Eq. (3.4.2)
Δp_{ENTRY}	pressure drop across the duct entrance region

Δp_F	cross-fan pressure difference, Eq. (3.4.1)
$\Delta p_{F,J}$	cross-fan pressure difference corresponding to point J on the fan curve
$\Delta p_{F,SOLN}$	value of ΔpF for a valid solution to the fan/duct flow problem
$\Delta p_{F,0}$	solution to $f(\Delta p_{F,0}) = 0$, Eq. (3.4.24)
Δp_N	Δp at y_N
Δp_{SYSTEM}	$\delta p_{SYSTEM,1} - \delta p_{SYSTEM,2}$
$\Delta p_{1,2}$	$p_1 - p_2$ at a specified y
ΔT_{EPS}	minimum temperature difference required for layer initiation
ΔT_{PLUME}	$\lvert T_{PLUME} - T_L \rvert$
$\Delta \rho$	$\rho_1 - \rho_2$
δ	Eq. (2.2.1)
δp_{DUCT}	pressure, relative to the datum pressure at a location somewhat inside the entry region of a forced ventilation duct
$\delta p_{FLOOR,i}$	$p_{FLOOR,i} - p_{DATUM}$
$\delta p_{F,1}$ [$\delta p_{F,2}$]	pressure, relative to the datum pressure, measured at fan inlet [outlet] section
δp_i	$p_i - p_{FLOOR,i}$
$\delta p_{QUIESCENT}$ [δp_{WIND}]	outside pressure, relative to the datum pressure, local to the vent in a quiescent [wind] environment
δp_{REF}	pressure of ambient, relative to datum pressure, at elevation y_{REF}
δp_{REFNEW}	new value for δp_{REF}, Eq. (4.5.2)
$\delta p_{SYSTEM,1}$ [$\delta p_{SYSTEM,2}$]	pressure, relative to the datum pressure, measured at fan/duct system inlet [outlet] endpoint
ϵ	$\Delta p/p_1$
$\tilde{\epsilon}$	ϵ at $\tilde{y}$
λ	a constant, Eq. (3.3.23)

λ_R	effective fraction of $\dot{Q}$ radiated from the combustion zone and the plume
λ_T	total fraction of $\dot{Q}$ lost to the bounding surfaces of fire room
λ_V	fraction of a penetrating flow slab's "enthalpy of buoyancy" [see Eq. (3.3.42)] transferred to the surfaces of the receiving room
ρ	density of the layer at $\hat{y}$
ρ_{AMB}	density of ambient
ρ_{DUCT}	density of flow in the duct
$\rho_{DUCT,1}$ [$\rho_{DUCT,2}$]	density of flow in the duct if its source is room 1 [room 2]
ρ_{PEN}	density of a flow slab as it penetrates the receiving room
ρ_U [ρ_L]	density of upper [lower] layer in a room
$\rho_{U,i}$ [$\rho_{L,i}$]	density of upper [lower] layer in room i
ρ_1 [ρ_2]	density in room 1 [room 2] at the elevation of a vent flow slab

<u>subscripts</u>

iREC	index of room receiving a flow slab
iFR	index of room from which fan/duct system flow is extracted
iTO	index of room to which fan/duct system flow is delivered

APPENDIX - Derivation of the Generic Equation Set for An Arbitrary Room

Consider an arbitrary room i of a simulated facility. Define V_i as the fixed volume of the room and $V_{U,i}$ as the changing volume of its upper layer, i.e., $V_i - V_{U,i}$ is the volume of the lower layer. Also, consistent with the definitions in Section 2.1, $M_{U,i}$, $M_{L,i}$ and $P_{k,U,i}$, $P_{k,L,i}$ are defined as the total instantaneous mass and amount of product of combustion k in the upper and lower layers, respectively.

In this Appendix, the generic equation set for the room will be derived in terms of the solution variables $M_{U,i}$, $M_{L,i}$, $P_{k,U,i}$, $P_{k,L,i}$, $V_{U,i}$, and $\delta p_{FLOOR,i}$.

Conservation of Mass:

Conservation of mass in the upper and lower layers requires that

$$dM_{U,i}/dt = \dot{M}_{U,i} \qquad (A.1)$$

$$dM_{L,i}/dt = \dot{M}_{L,i} \qquad (A.2)$$

Consistent with the definitions in Section 2.1, the terms $\dot{M}_{U,i}$ and $\dot{M}_{L,i}$ on the right hand side of Eqs. (A.1) and (A.2) each represent the sum of individual mass flow rate contributions to the layers from all plumes, jets, sources, etc. (positive values mean net rate of flow is into the layer). The terms $\dot{P}_{k,U,i}$, $\dot{P}_{k,L,i}$, and $\dot{Q}_{U,i}$, $\dot{Q}_{L,i}$, to be introduced below, will represent analogous product and enthalpy flow rate contributions, respectively.

Conservation of Energy:

Conservation of energy in the upper and lower layers requires that

$$d[M_{U,i}C_vT_{U,i}]/dt + p_{FLOOR,i}dV_{U,i}/dt = \dot{Q}_{U,i} \qquad (A.3)$$

$$d[M_{L,i}C_vT_{L,i}]/dt - p_{FLOOR,i}dV_{U,i}/dt = \dot{Q}_{L,i} \qquad (A.4)$$

where C_v is the specific heat at constant volume, assumed here to always have a constant value associated with a perfect-gas model of air; $p_{FLOOR,i}$ is the assumed-uniform absolute hydrostatic pressure at the floor elevation of the room; and, with the use of the approximation of Eq. (2.2.3), the right-hand terms on the left-hand sides of Eqs. (A.3) and (A.4) represent the rate at which pressure forces do work on the moving layer interface.

Conservation of Products of Combustion:

Conservation of product of combustion k in the upper and lower layers requires

$$dP_{k,U,i}/dt = \dot{P}_{k,U,i} \tag{A.5}$$

$$dP_{k,L,i}/dt = \dot{P}_{k,L,i} \tag{A.6}$$

Equation of State and the Layer Densities, Temperatures, and Concentrations of Products of Combustion:

Applying uniformly the equation of state for air and using again Eq. (2.2.3) leads to

$$p_{FLOOR,i} = \rho_{U,i}T_{U,i}R = \rho_{L,i}T_{L,i}R \tag{A.7}$$

where R is the gas constant for air and $\rho_{U,i}$ and $\rho_{L,i}$, the density of the upper and lower layer, respectively would be computed according to their definitions from the solution variables $M_{U,i}$, $M_{L,i}$, and $V_{U,i}$ (an explicit equation for $V_{U,i}$ is presented below).

$$\rho_{U,i} = M_{U,i}/V_{U,i} \tag{A.8}$$

$$\rho_{L,i} = M_{L,i}/(V_i - V_{U,i}) \tag{A.9}$$

Having computed the densities, the absolute temperatures of the upper and lower layer, $T_{U,i}$ and $T_{L,i}$, respectively, can be computed from the solution variable $p_{FLOOR,i}$ using Eq. (A.7).

$$T_{U,i} = p_{FLOOR,i}/(\rho_{U,i}R) \tag{A.10}$$

$$T_{L,i} = p_{FLOOR,i}/(\rho_{L,i}R) \tag{A.11}$$

Finally, $c_{k,U,i}$ and $c_{k,L,i}$, the concentration of product k per unit mass of the upper and lower layer, respectively, is related to the solution variables $M_{U,i}$, $M_{L,i}$, $P_{k,U,i}$, $P_{k,L,i}$ according to

$$c_{k,U,i} = P_{k,U,i}/M_{U,i} \tag{A.12}$$

$$c_{k,L,i} = P_{k,L,i}/M_{L,i} \tag{A.13}$$

Deriving Equations for the Solution Variables $p_{FLOOR,i}$ and $V_{U,i}$ or $y_{LAYER,i}$:

Using Eq. (A.7) with Eqs. (A.8) and (A.9) to replace $M_{U,i}T_{U,i}$ and $M_{L,i}T_{L,i}$ in Eqs. (A.3) and (A.4) leads to

$$(C_v/R)d[p_{FLOOR,i}V_{U,i}]/dt + p_{FLOOR,i}dV_{U,i}/dt = \dot{Q}_{U,i} \quad \text{(A.3')}$$

$$(C_v/R)d[p_{FLOOR,i}(V_i - V_{U,i})]/dt - p_{FLOOR,i}dV_{U,i}/dt = \dot{Q}_{L,i} \quad \text{(A.4')}$$

Now add Eqs. (A.3') and (A.4') and use the result to replace Eq. (A.4')

$$dp_{FLOOR,i}/dt = [R/(C_vV_i)](\dot{Q}_{U,i} + \dot{Q}_{L,i}) \quad \text{(A.4'')}$$

Expanding Eq. (A.3') leads to

$$(C_v/R)V_{U,i}dp_{FLOOR,i}/dt + (C_v/R)p_{FLOOR,i}dV_{U,i}/dt + p_{FLOOR,i}dV_{U,i}/dt = \dot{Q}_{U,i}$$

Collecting coefficients of $dV_{U,i}/dt$ in the above and using Eq. (A.4'') results in the following equation for $V_{U,i}$ which is used to replace Eq. (A.3'):

$$dV_{U,i}dt = [(1 - V_{U,i}/V_i)\dot{Q}_{U,i} - (V_{U,i}/V_i)\dot{Q}_{L,i}]/[p_{FLOOR,i}(1 + C_v/R)] \quad \text{(A.3'')}$$

Introducing γ, the ratio of specific heats,

$$\gamma \equiv C_p/C_v = 1 + R/C_v \quad \text{(A.14)}$$

Eqs. (A.3'') and (A.4'') are written finally as

$$dV_{U,i}/dt = [(\gamma-1)/(\gamma p_{FLOOR,i})][(1 - V_{U,i}/V_i)\dot{Q}_{U,i} - (V_{U,i}/V_i)\dot{Q}_{L,i}] \quad \text{(A.3''')}$$

$$dp_{FLOOR,i}/dt = [(\gamma-1)/V_i](\dot{Q}_{U,i} + \dot{Q}_{L,i}) \quad \text{(A.4''')}$$

For rooms i of a facility with horizontal sectional areas, A_i, which are uniform with elevation, (i.e., for rectangular rooms with vertical walls and for other right cylindrical rooms), Eq. (A.3''') can be written in terms the solution variable $y_{LAYER,i}$, the elevation of the interface separating the upper and lower layers, instead of $V_{U,i}$. Thus, if

$$V_i = A_i(y_{CEILING,i} - y_{FLOOR,i}) \tag{A.15}$$

$$V_{U,i} = A_i(y_{CEILING,i} - y_{LAYER,i}) \tag{A.16}$$

where $y_{CEILING,i}$ and $y_{FLOOR,i}$ are the fixed elevations of the ceiling and floor, respectively, then Eq. (A.3''') can be replaced by

$$dy_{LAYER,i}/dt = [(\gamma-1)/(\gamma p_{FLOOR,i}V_i)][(y_{CEILING,i} - y_{LAYER,i})\dot{Q}_{L,i} - (y_{LAYER,i} - y_{FLOOR,i})\dot{Q}_{U,i}] \qquad \text{(A.3'''')}$$

<u>The Generic Equation Set</u>:

The final set of generic equations for the solution variables $M_{U,i}$, $M_{L,i}$, $V_{U,i}$, $p_{FLOOR,i}$, $P_{k,U,i}$, and $P_{k,L,i}$ is Eqs. (A.1), (A.2), (A.3'''), (A.4'''), (A.5), and (A.6), respectively. Also, the derived variables $\rho_{U,i}$, $\rho_{L,i}$, $T_{U,i}$, $T_{L,i}$, $c_{k,U,i}$, and $c_{k,L,i}$ are computed from Eqs. (A.8)-(A.13).

For right cylindrical rooms where Eqs. (A.15) and (A.16) are satisfied, the Variable $y_{LAYER,i}$ can be used instead of the variable $V_{U,i}$, in which case Eq. (A.3''') is replaced by Eq. (A.3'''').

<u>The Perturbation-Pressure Variable</u>:

Typical fire scenarios involve $p_{FLOOR,i}$ values which vary a relatively small amount from a datum absolute pressure, p_{DATUM}. For example, if p_{DATUM} in a problem is taken as the local atmospheric pressure at ground elevation, of the order of 10^5 pascals, then typical variations of the $p_{FLOOR,i}$s from p_{DATUM} will only be of the order of 10^2 or less. For this reason, a new transformed pressure variable,

$$\delta p_{FLOOR,i} = p_{FLOOR,i} - p_{DATUM} \tag{A.17}$$

will lead typically to a higher level of accuracy in the computation of $p_{FLOOR,i}$. The perturbation-pressure variable $\delta p_{FLOOR,i}$ is adopted as a new solution variable to replace $p_{FLOOR,i}$.

The generic equation set using the perturbation-pressure is presented in Section 2.3.

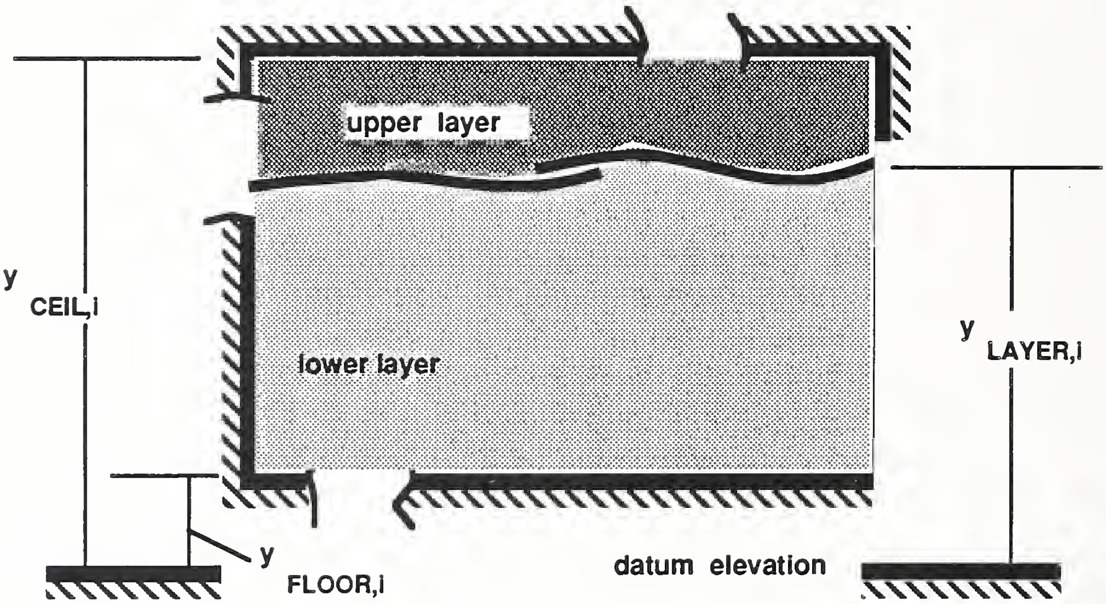

Figure 2.1. The two-layer environment for an arbitrary room of a multi-room facility.

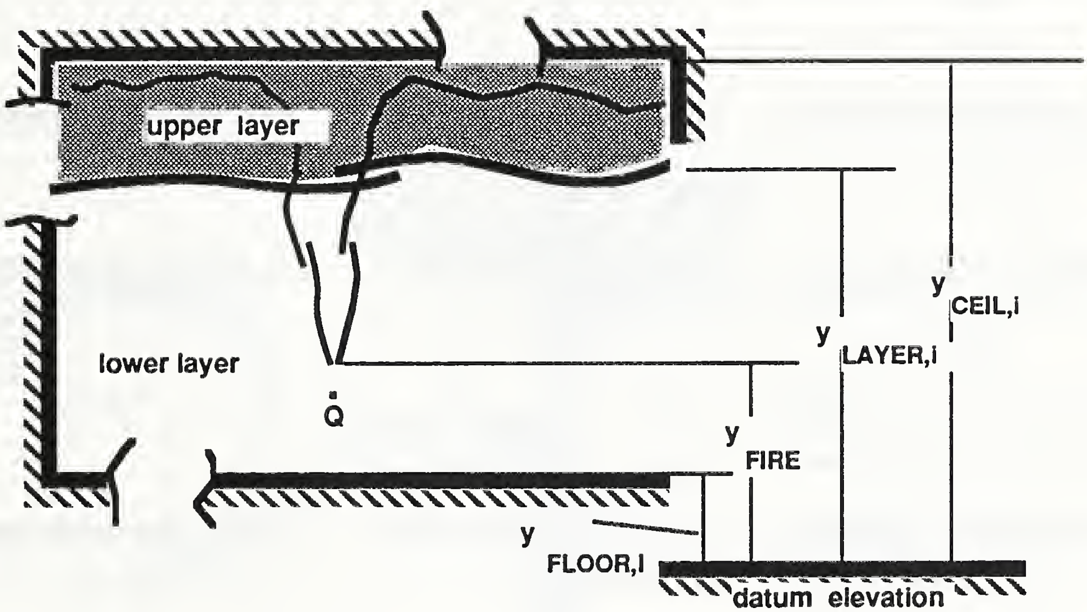

Figure 3.2.1. A room of fire origin.

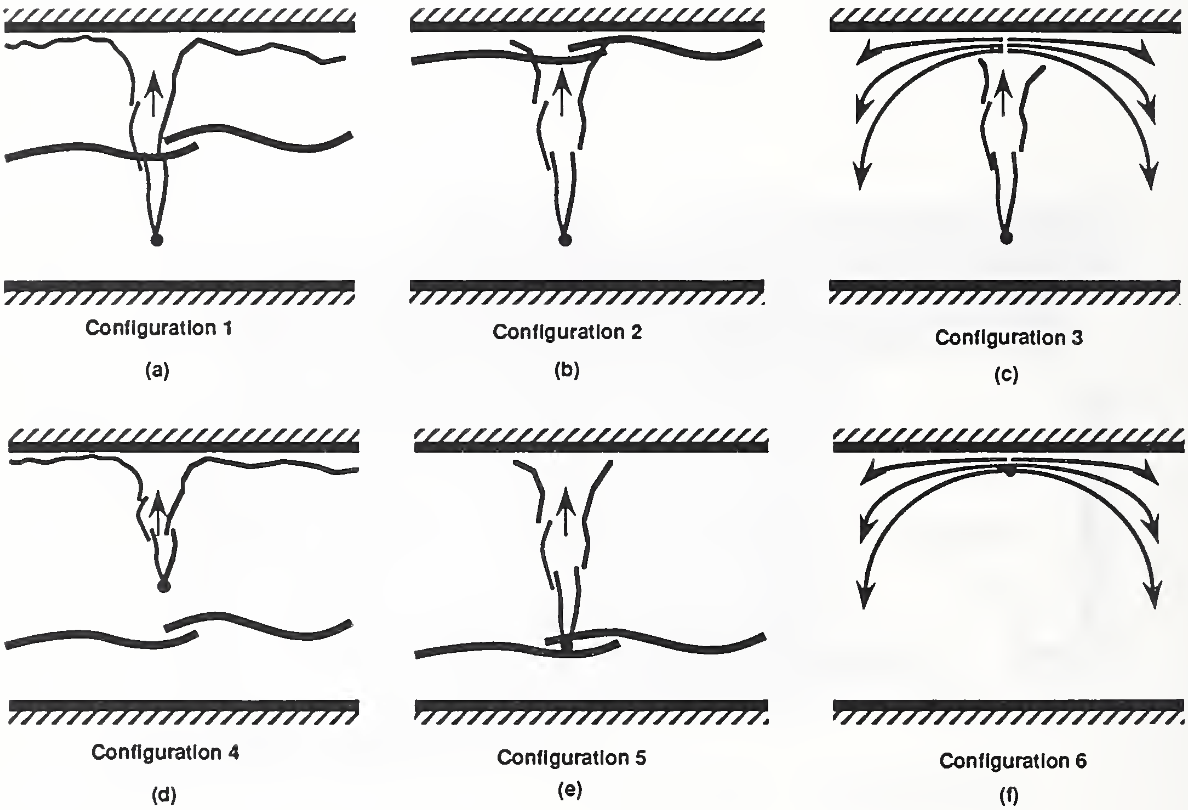

Figure 3.2.2. Configurations for the fire, the plume and the elevations of interface and ceiling.

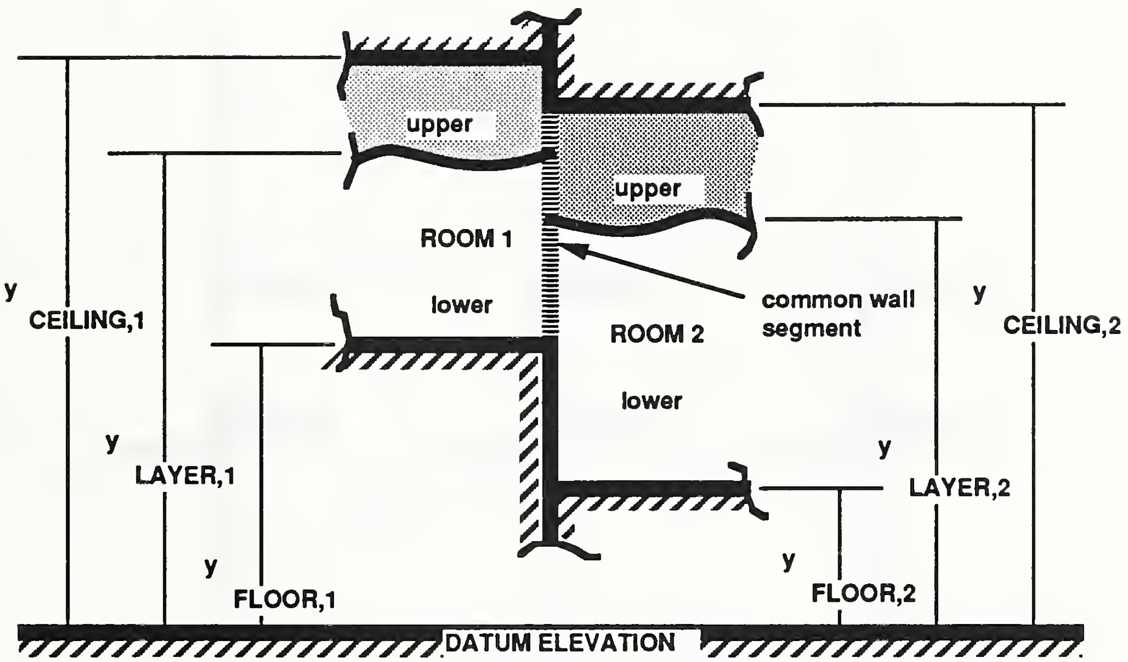

Figure 3.3.1. The fire-generated environment in two adjacent rooms.

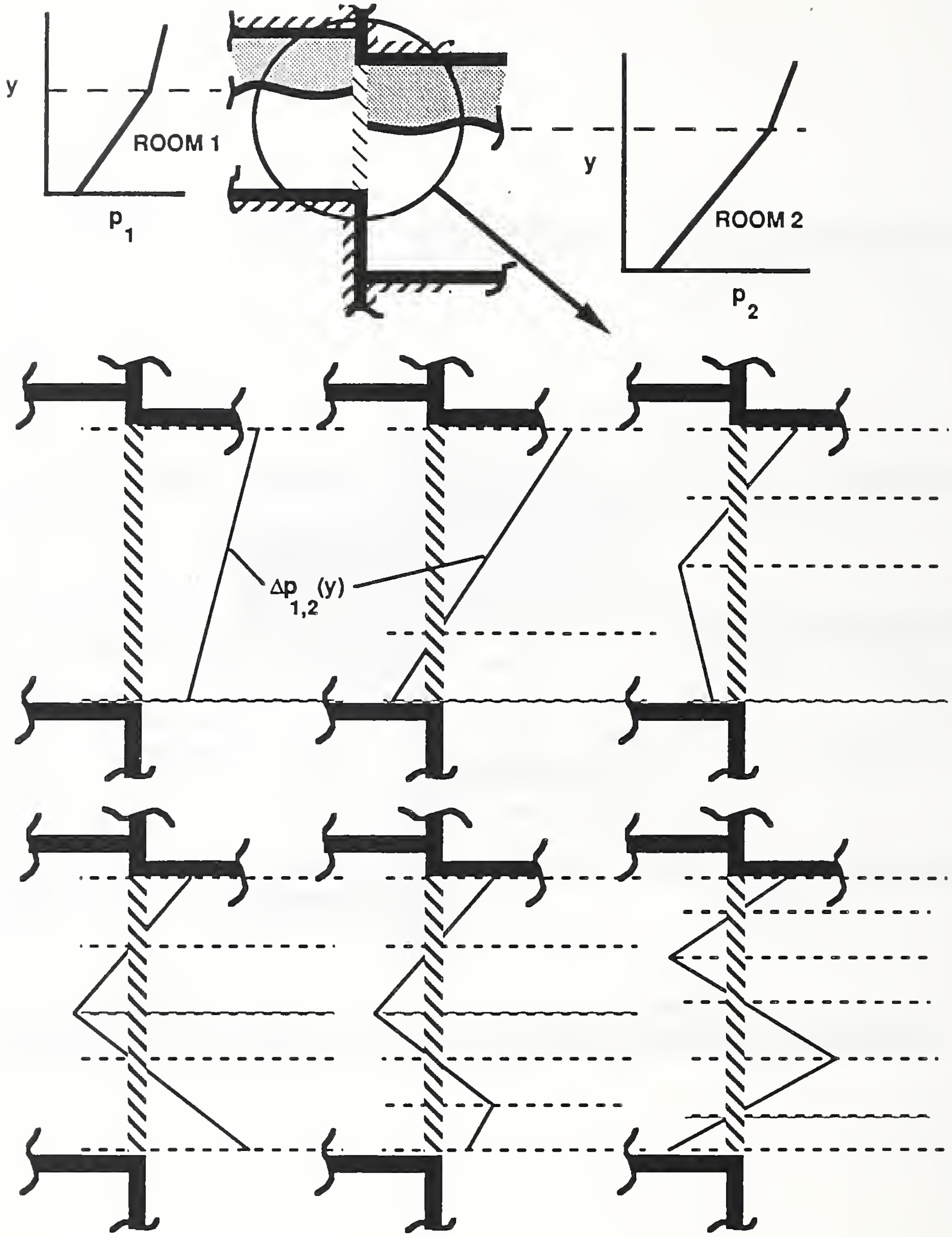

Figure 3.3.2. Possible distributions of $\Delta p_{1,2} = p_1 - p_2$ for a common-wall segment.

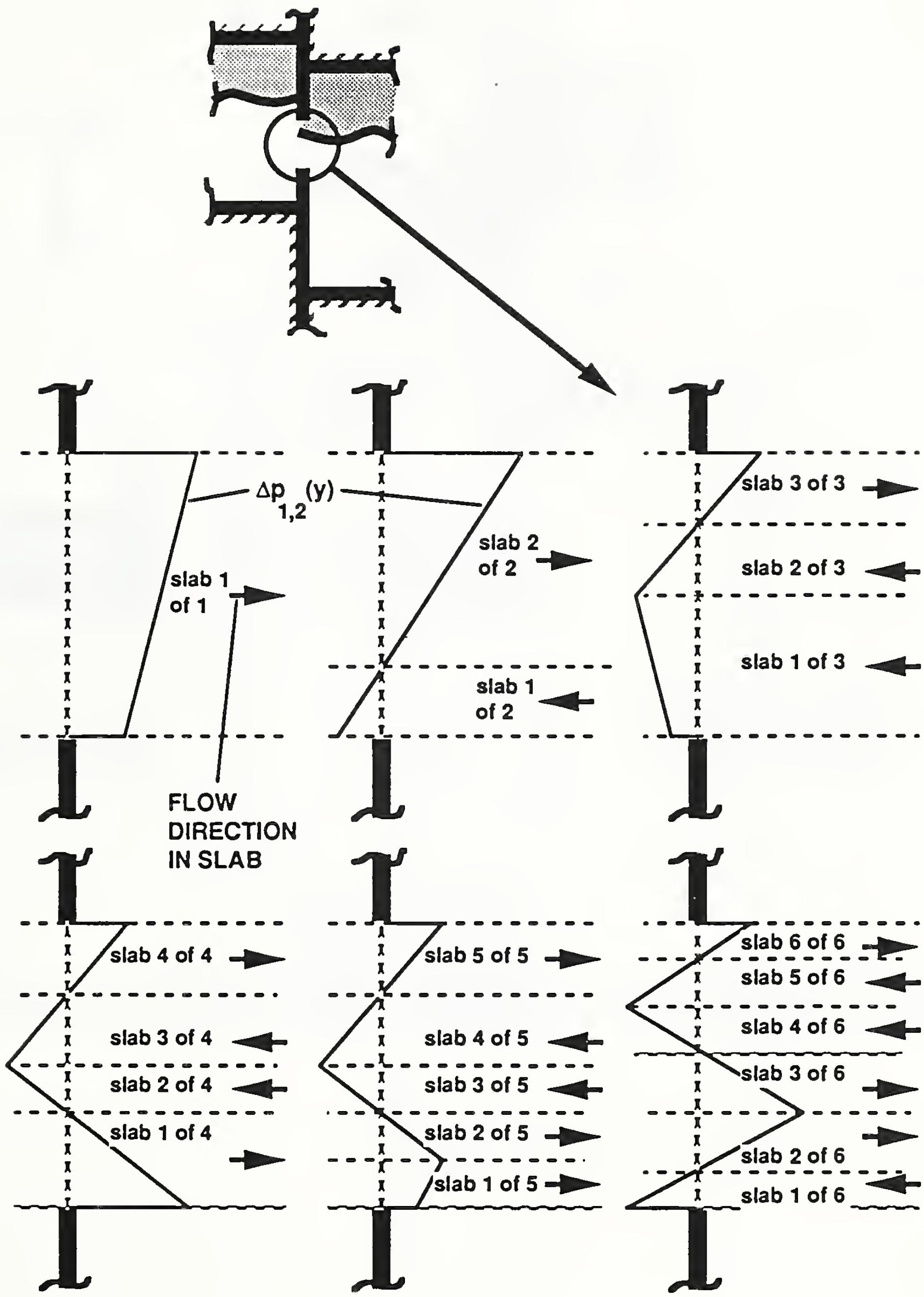

Figure 3.3.3. Possible distributions of $\Delta p_{1,2} = p_1 - p_2$ for a single vent and the flow directions of its uniform-property flow slabs.

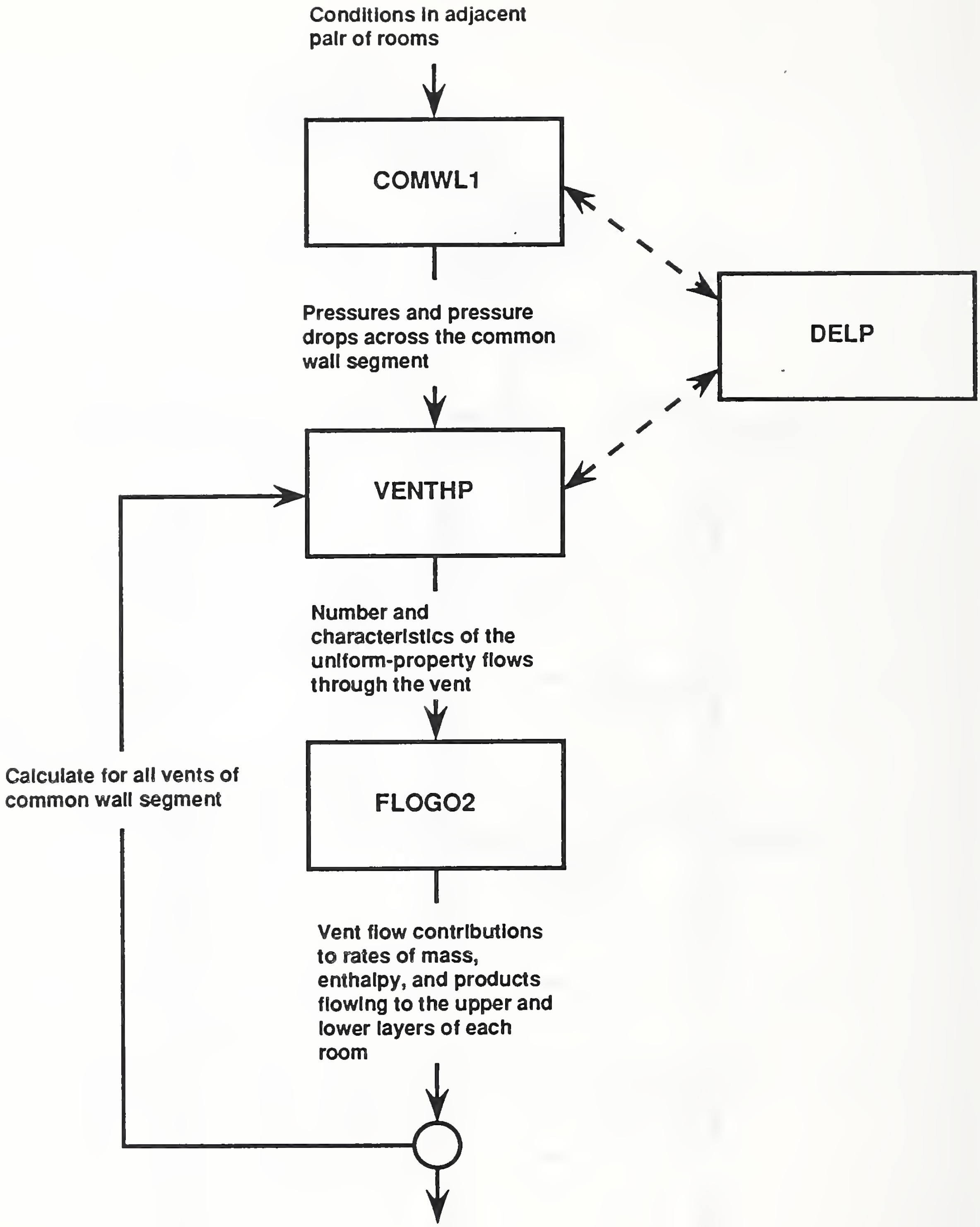

Figure 3.3.4. Use of the algorithms DELP, COMWL1, VENTHP, and FLOGO2 to carry out rates of exchange of mass, enthalpy, oxygen, and other products of combustion through vertical natural vents of a multi-room facility.

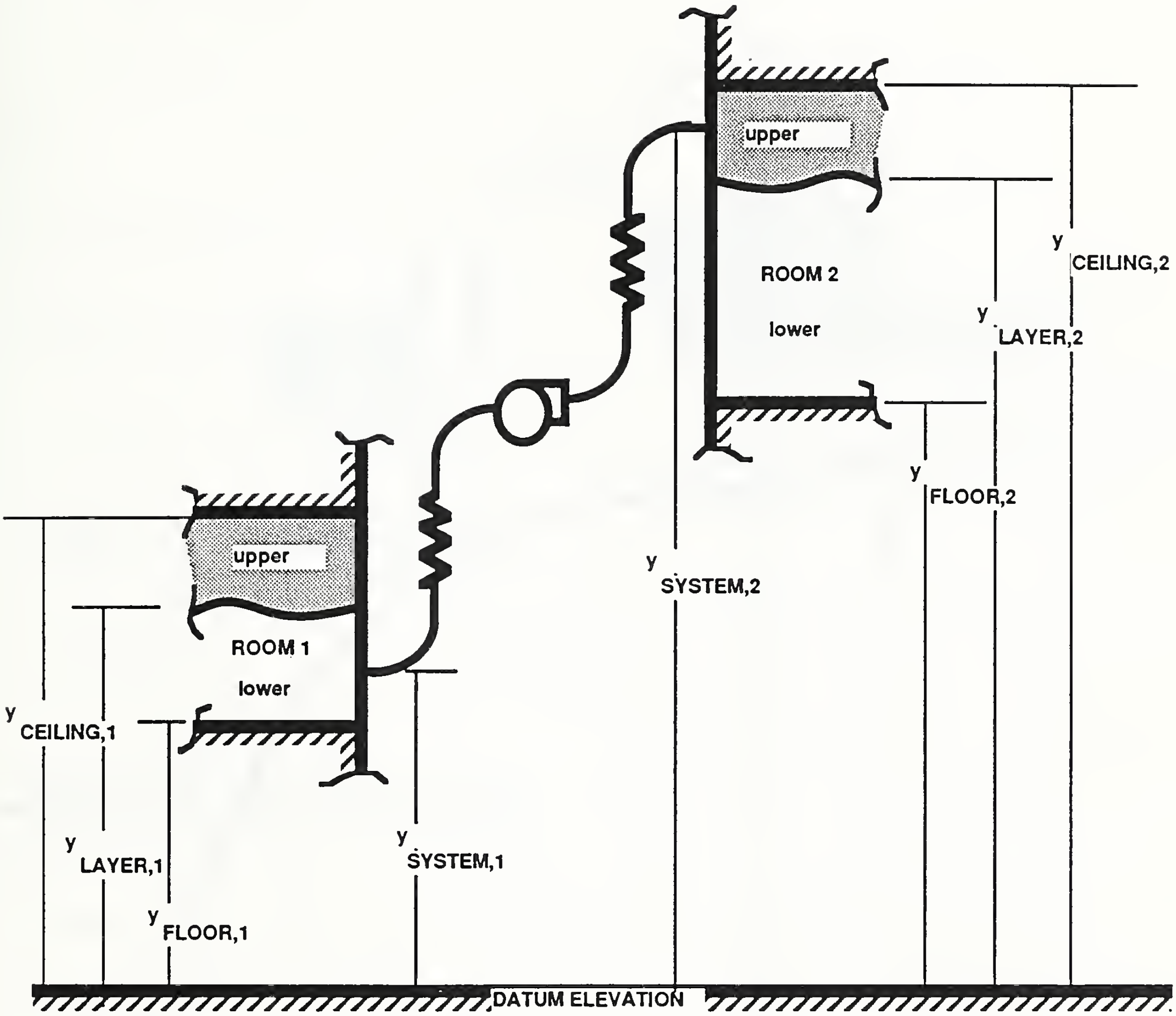

Figure 3.4.1. The fire-generated environment in two rooms connected by a fan/duct system.

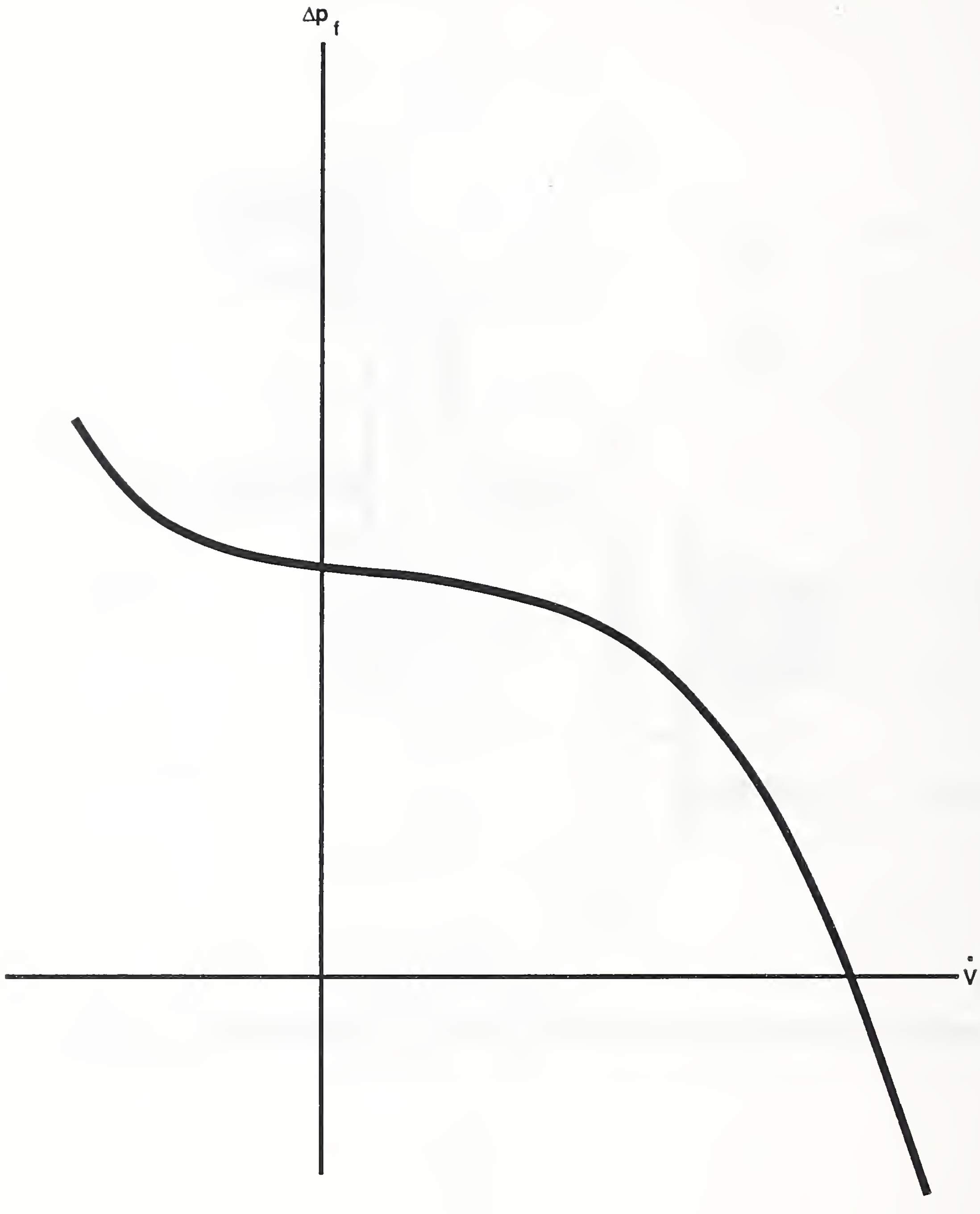

Figure 3.4.2. A sketch of a generic fan operating curve which increases monotonically in volume flow rate with decreasing cross-fan pressure difference.

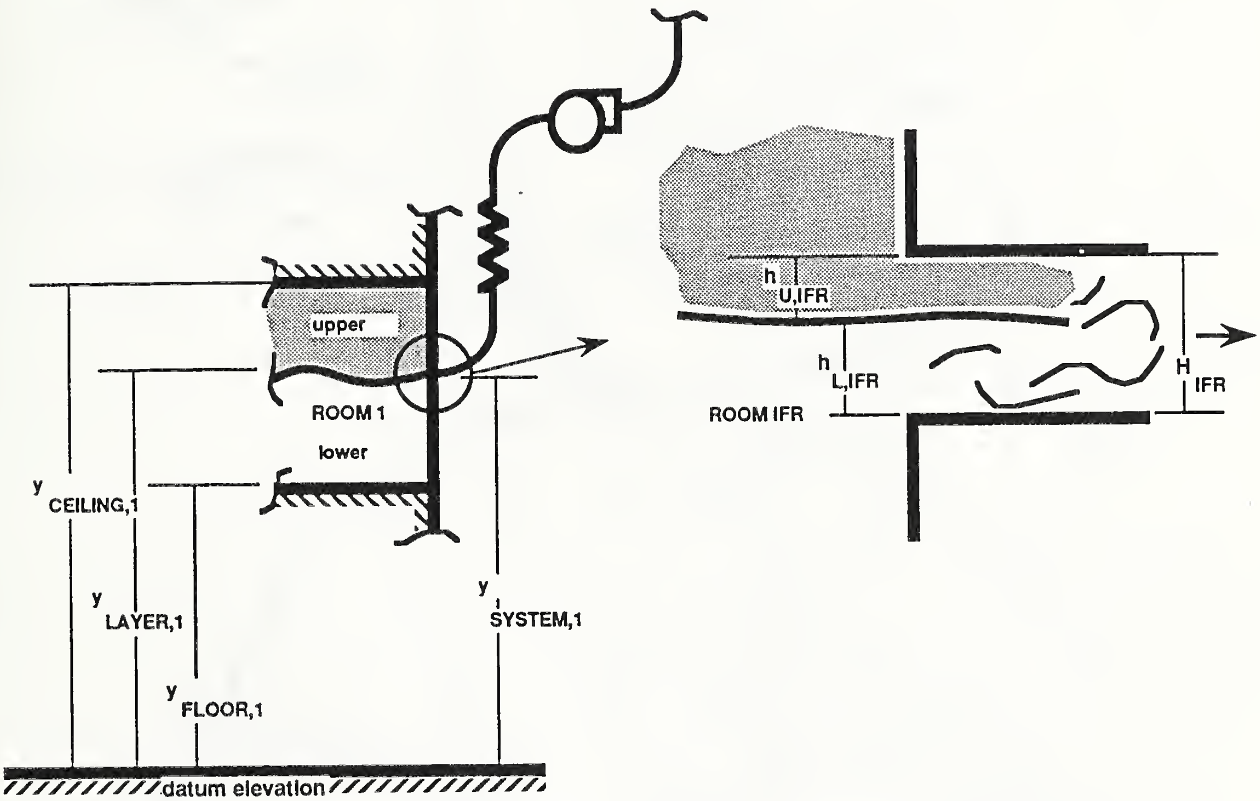

Figure 3.4.3. An illustration of the flow entering the duct in room iFR when the layer interface is between the top and bottom of the vent opening.

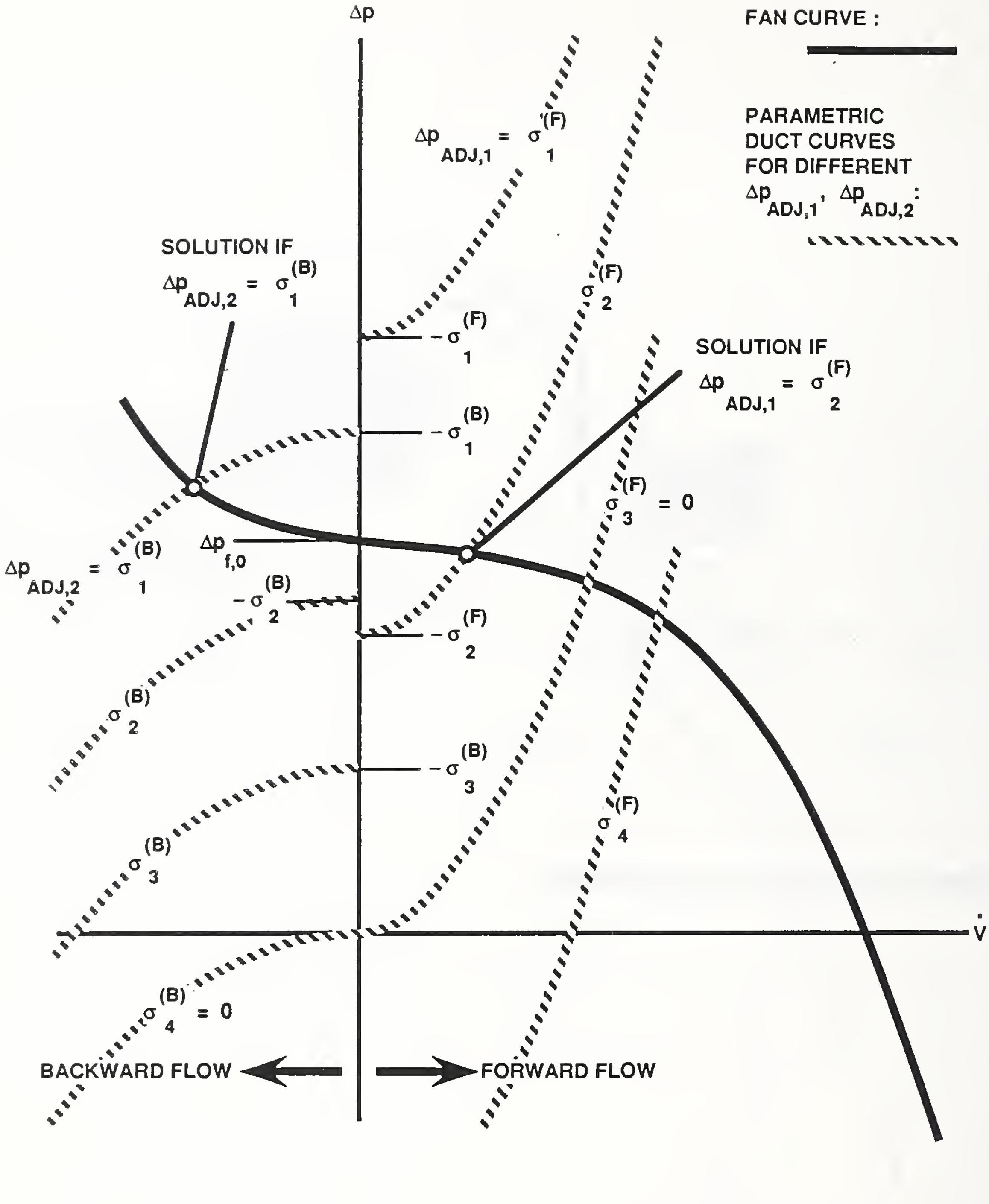

Figure 3.4.4. Graphical presentation of the problem of solving Eq. (3.4.24) and finding the direction and flow rate through a fan/duct system.

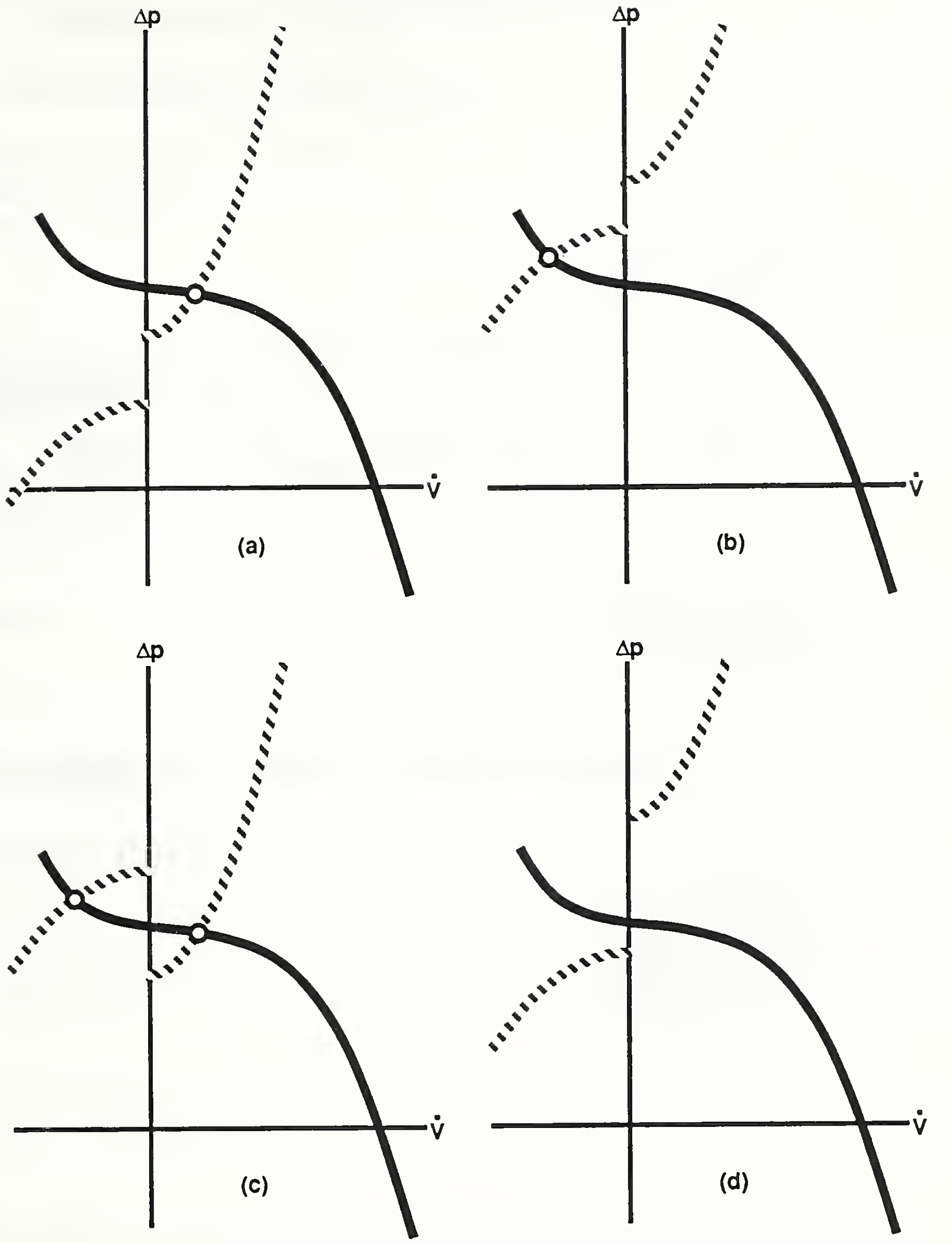

Figure 3.4.5. Graphical presentation from Figure 3.4.4 of the four classes of solution for flow rate through the fan/duct system: (a) single forward-flow solution and no backward-flow solution, (b) single backward-flow solution and no forward-flow solution, (c) one forward-flow solution and one backward-flow solution, and (d) no solutions.

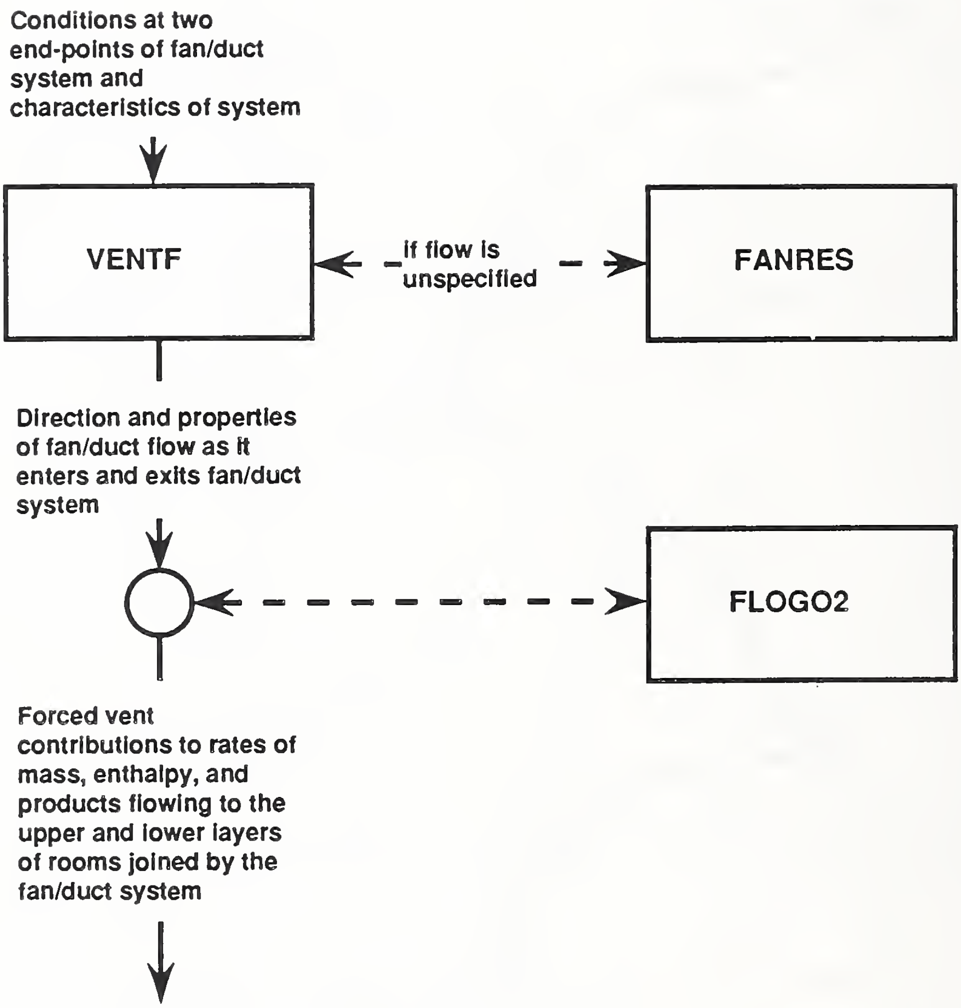

Figure 3.4.6. Use of the algorithms VENTF, FANRES, and FLOGO2 to carry out rates of exchange of mass, enthalpy, oxygen, and other products of combustion through fan/duct forced ventilation systems connecting two rooms of a multi-room facility.

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A project was carried out at The National Institute of Standards and Technology (NIST) to study the feasibility of developing a new-generation, multi-room, compartment fire model computer code, called the Consolidated Compartment Fire Model (CCFM) computer code. The idea was that such a code would consolidate past progress in zone-type compartment fire modeling, and allow readily for integration of future advances with the greatest possible flexibility. The project lead to the development of a prototype multi-room CCFM product called CCFM.VENTS.

This is Part I of a four-part report which documents the above effort. Introductory remarks discuss the generic features of the CCFM and the specific features of CCFM.VENTS. The main objective of this Part I document is to present a comprehensive description of the governing equations of CCFM.VENTS and their technical basis.

The other three parts of this report are: Part II: Software Reference Guide; Part III: Catalog of Algorithms and Subroutines; and Part IV: User Reference Guide.

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