NISTIR 4402

AN ALGORITHM AND ASSOCIATED COMPUTER SUBROUTINE FOR CALCULATING FLOW THROUGH A HORIZONTAL CEILING/FLOOR VENT IN A ZONE-TYPE COMPARTMENT FIRE MODEL

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October 1990

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An Algorithm and Associated Computer Subroutine For Calculating Flow Through a Horizontal Ceiling/Floor Vent in a Zone-Type Compartment Fire Model

Leonard Y. Cooper

ABSTRACT

An algorithm and associated computer subroutine is presented for calculating the effects on two-layer compartment fire environments of the quasi-steady flow through a horizontal vent connecting two spaces. The two spaces can be either two inside rooms of a multi-room facility or one inside room and the outside ambient environment local to the vent. The description of the flow through the vent is determined by combining considerations of 1) the unidirectional-type of flow driven by a cross-vent pressure difference and, when appropriate, 2) the exchange-type of flow induced when the fluid configuration across the vent is unstable, i.e., when a relatively cool, dense gas in the upper space overlays a less dense gas in the lower space. In the algorithm, calculation of the rates of flow exchange between the two spaces is based on a previously reported theory. Characteristics of the geometry and the instantaneous environments of the two spaces are assumed to be known and specified as inputs. The outputs calculated by the algorithm/subroutine are the rates and the properties of the vent flow at the elevation of the vent as it enters the top space from the bottom space and/or as it enters the bottom space from the top space. Rates of mass, enthalpy, and products of combustion extracted by the vent flows from upper and lower layers of inside room environments and from outside ambient spaces are determined explicitly. The algorithm/subroutine is called VENTCF. The computer subroutine is written in FORTRAN 77. The subroutine is completely modular, and it is suitable for general use in two-layer, multi-room, zone-type fire model computer codes. It has been tested over a wide range of input variables and these tests are described.

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

1. Introduction

This work presents an algorithm and associated computer subroutine, called VENTCF. The purpose of VENTCF is to calculate the instantaneous effects on two-layer fire environments of the quasi-steady flow through a horizontal vent connecting two spaces involved in a compartment fire. The subroutine is designed to be modular and easy to integrate into any two-layer zone-type compartment fire model.

Flow through horizontal vents can be of particular importance in fires on ships. Because of the generic design of ships, compartments of fire origin can be connected by horizontal vents to adjacent spaces on a deck below and/or above. As examples of this consider the case of a fire in an otherwise poorly-ventilated hold of a ship during the staging of fire-fighting activities initiated through a horizontal vent from the deck above, or the case of a fire in a compartment on an upper deck which is vented through an overhead horizontal penetration to the outside environment on the top deck. Knowledge of the flow exchanges through such vents are important since the oxygen convected along with these flows can be critical in determining the growth (or decay) of the fire. Also, deck-to-deck flows through such horizontal vents can play a major role in determining the smoke spread and the resulting development of potentially hazardous conditions thoughout the rest of the ship. A major motivation for this work is to provide a computational tool that can be used to predict these phenomena.

Consider the flow through a horizontal ceiling/floor vent connecting two spaces, one on top of the other, involved in a fire-generated environment. The two spaces can be two inside rooms of a multi-room facility, as depicted in Figure 1a of the APPENDIX, or they can be comprised of one inside room of a facility and one outside space, either above or below the room, which is used to simulate conditions, local to the vent, of the outside ambient. The latter configurations are depicted in Figures 1b and 1c of the APPENDIX, respectively.

The flow through the vent is determined by a model which takes into account traditional considerations of flow due to a cross-vent pressure difference (see, e.g., reference [1]) and, when appropriate, flows induced when existing fluid configurations are unstable, i.e., when a relatively cool, dense gas in the upper space overlays an elevated temperature and relatively less dense gas in the lower space. Whereas a non-zero cross-vent pressure difference always tends to drive a unidirectional flow through the vent, from the higher- to the lower-pressure side, flow induced by an unstable fluid density configuration tends to lead to an exchange-type of flow, with fluid in the lower space rising into the upper space and flow from the upper space dropping into the lower space. In the present algorithm, the actual calculation of the flow between the two spaces is based on the previously developed theory presented in reference [2].

Determined explicitly by the present algorithm/subroutine are the net instantaneous rates of addition of mass, enthalpy, and products of combustion of interest and the properties of the vent flows to each of the spaces at the elevation of the vent. A determination of where such flows go once they enter the recieving spaces would be obtained with the use of additional algorithms and associated subroutines. These additional algorithms, which would use the output of the present algorithm/subroutine, would be based on considerations beyond the scope of the present work.

A flow through the horizontal vent which enters one of the spaces joined by the vent is extracted from the other space. Depending on the configuration of the two spaces, the direction of the flow, and, in the case of inside rooms, the elevation of the two-layer interface (i.e., at the floor, ceiling, or in-between), the present algorithm determines explicitly the rates of extraction of mass, enthalpy, and products of combustion from the upper and lower layers of the one or two inside rooms and/or from an outside ambient space that are joined by the vent under consideration. Along with other components of flow to or from the layers of the inside rooms, determined with the use of other algorithms, these rates would be used to continue in time the solution to the equations of the overall fire model. These are the equations used to simulate mathematically the facility's overall dynamic fire environment.

2. The Algorithm and Associated Subroutine VENTCF for Calculating the Effects of Flow Through Horizontal Ceiling/Floor Vents

The algorithm/subroutine VENTCF is presented here in the APPENDIX as a stand-alone document that can be inserted as a new entry into the catalog of modular algorithms and associated computer subroutines of reference [3]. That document is a grouping of algorithms/subroutines useful for simulating the physical phenomena in multi-room zone-type compartment fire model computer codes. Pagination of the present APPENDIX and of all entries of the reference [3] catalog is according to name of the particular algorithm/subroutine (in this case, VENTCF) and page number of the catalog entry.

The catalog of reference [3] was concieved of as a growing document where the entries would be available for general use by people interested in: developing or improving, for their own particular needs, a general or special-purpose multi-room zone-type compartment fire model; or predicting isolated compartment fire phenomena, for whatever reason. The present VENTCF algorithm/subroutine is the first new entry to the original reference-[3] document.

3. Format of the VENTCF Catalog Entry

The development, technology transfer, and use of a reference-[3]-type of catalog of algorithms and associated subroutines is enhanced by maintaining guidelines for a uniform format of algorithm/subroutine documentation. In this regard a prototype format was developed and used in all reference-[3] algorithm/subroutine catalog entries. The format, which is followed here, includes the following elements:

TITLE	-	Should indicate the main purpose of the algorithm/subroutine.
DESCRIPTION	-	General description of the algorithm.
OUTPUT	-	List of output variables, including definitions and units.
INPUT	-	List of input variables, including definitions and units.
CALCULATIONS	-	Concise description of the rules for obtaining the output variables from the input variables. This would include or refer explicitly to all equations required in the calculation. If other algorithms/subroutines are required, then these should be readily available and referenced.
SUBROUTINES USED	-	Listing of or explicit reference to each algorithm/subroutine used to carry out the calculations.
REFERENCES	-	A list of references.
SUBROUTINE VARIABLES	-	A cross-reference of all nomenclature (including units) introduced in the above sections to the nomenclature used in the FORTRAN computer subroutine.
PREPARED BY	-	Names of those who prepared the algorithm/subroutine and date of preparation.
SUBROUTINE	-	Listing of the computer subroutine. This would be well-commented and would include a summary of the purpose of the subroutine and definitions (including units) of its input and output variables.

The algorithm VENTCF and a listing of its associated computer subroutine is presented in the APPENDIX. The subroutine is coded in FORTRAN 77.

4. Testing of the Subroutine VENTCF

The subroutine VENTCF has not yet been incorporated into any full compartment fire model computer code. However, extensive parametric testing of the subroutine has been carried out. This testing will be described here.

A wide range of environment scenarios for each of the three basic configurations of Figure 1 of the Appendix were considered. For each configuration, parameters were varied in a manner as to simulate all possible combinations of the following:

a. for the two layers of an inside space: the usual case with two non-zero-thickness layers (i.e., layer interface between the ceiling and the floor), or one non-zero-thickness layer and one zero-thickness layer (i.e., layer interface at the ceiling or floor);

b. stable or unstable cross-vent density configuration;

c. the reference elevation for an outside space is above, at, or below the vent elevation;

d. 1.0 atmosphere reference pressure, $p_{REF,1}$, in the top space (i.e., $p_{DATUM} = 101325.$ pa with $\delta p_{REF,1} \equiv p_{REF,1} - p_{DATUM} = 0$) with reference pressure in the bottom space, $p_{REF,2}$, varying from 0.01 atmospheres to 2.0 atmospheres (i.e., $-0.99 p_{DATUM} < \delta p_{REF,2} \leq p_{DATUM}$); and

e. 1.0 atmosphere reference pressure, $p_{REF,2}$, in the bottom space (i.e., $p_{DATUM} = 101325.$ pa with $\delta p_{REF,2} \equiv p_{REF,2} - p_{DATUM} = 0$) with reference pressure in the top space, $p_{REF,1}$, varying from 0.01 atmospheres to 2.0 atmospheres (i.e., $-0.99 p_{DATUM} < \delta p_{REF,1} \leq p_{DATUM}$)

Five distinct elevations (relative to a datum elevation), y_N, N = 1 to 5, and three distinct densities, ρ_N, N = 1 to 3, were required to construct the environment scenarios. These were chosen to be:

$$\begin{aligned} &y_1 = 0.0\text{m};\quad y_2 = 1.5\text{m};\quad y_3 = 3.0\text{m};\quad y_4 = 4.5\text{m};\quad y_5 = 6.0\text{m} \\ &\rho_1 = 1.00\text{kg/m}^3;\quad \rho_2 = 0.50\text{kg/m}^3;\quad \rho_3 = 0.25\text{kg/m}^3 \end{aligned} \tag{1}$$

When the environment of an inside room involved two layers, the layer densities were specified to be in a stable configuration (i.e., a low density layer above a high density layer).

Table 1 identifies all configurations and environment specifications that were used in the parametric testing of the subroutine. This involved 162 basic "Cases." Each Case involved a separate parametric study of over two thousand calls to the subroutine. These covered the above pressure range of either condition d. or condition e. The calls involved incremental changes of the relative reference pressures, $\delta p_{REF,1}$ for condition e and $\delta p_{REF,2}$ for condition d, which were small enough to reveal details of the exchange-flow phenomena, these being sensitive to fractional-pascal-level variations in cross-vent pressure differences.

For each Case, Table 1 identifies values of the parameters which define the configuration of the two spaces, as illustrated in Figure 1 of the Appendix, and the states of the environments in the spaces. These are the parameters used to call the subroutine. (The reader is referred to the NOMENCLATURE Section for explaination of terms used in the table.) Also explicitly identified in the table are those Cases which involve unstable cross-vent density configurations. When cross-vent pressure differences are small enough in magnitude, such Cases lead to the exchange-flow phenomena which are of particular interest.

Presented in Figures 1 and 2 are plots of the calculated mass flow rates to upper room 1, $\dot{M}_{VENT,1}$, and to lower room 2, $\dot{M}_{VENT,2}$, as functions of the computed cross-vent pressure difference, Δp, for Cases 28, 29, and 30. As in Eq. (2) of the Appendix, Δp, an output variable of the subroutine, is defined as

$$\Delta p = p_2 - p_1 \tag{2}$$

where p_1 and p_2 are the pressures in the top and bottom spaces at the elevation of the vent (see Figure 2 of the Appendix).

As indicated Table 1, Cases 28, 29, and 30 involve two inside rooms where, as depicted in Figure 1a of the Appendix, both of these have an upper and a lower layer. Case 28 involves a neutrally-stable cross-vent density configuration since the density immediately above the vent (in the lower layer of room 1), $\rho_{L,1} = \rho_2 = 0.50\text{kg/m}^3$, is identical to the density immediately below the vent (in the upper layer of room 2). Cases 29 and 30 involve an unstable cross-vent density configuration since the density immediately above the vent, $\rho_{L,1} = \rho_1 = 1.0\text{kg/m}^3$, is greater than the density immediately below the vent, $\rho_{U,2} = \rho_2 = 0.50\text{kg/m}^3$.

The scale of the Δp abscissa of Figure 1 is relatively coarse, and the plots reveal the calculated mass flow rates through the vent as a result of large cross-vent pressure differences, i.e., when effects of compressibility become significant as could be the case, for example, for fires in nearly-hermetically-sealed facilities. In the figure, the sharp breaks in the $\dot{M}_{VENT,1}$ and $\dot{M}_{VENT,2}$ plots for Cases 28 and 30 and for Case 29, respectively, correspond to cross-vent pressure differences, Δp, which separate choked from unchoked flow through the vent. Define p_{HIGH} and p_{LOW} as the absolute pressures on the high- and low-pressure side of the vent, respectively. Then, consistent with Eqs. (7)-(15) of the Appendix, such choking occurs for air (i.e., $\gamma = 1.40$) when [4,5]

$$p_{LOW}/p_{HIGH} \le [2/(\gamma + 1)]^{\gamma/(\gamma - 1)} = 0.528 \tag{3}$$

As indicated in Figure 1, for Case 29 the parameters specified in Table 1 lead to a prediction of choked vent flow from room 1 to room 2 approximately when

$\Delta p \leq -0.472 p_{DATUM} = -0.478(10^5)$pa. Also, for Cases 28 and 30, choked flow from room 2 to room 1 is predicted when $\Delta p \geq 0.472 p_{DATUM} = 0.478(10^5)$pa.

The scale of the abscissa of Figure 2 is relatively fine, and the plots reveal the calculated mass flow rates through the vent when the cross-vent pressure differences are at or close to zero. Since the Case-28 density configuration is neutrally-stable, i.e., only uni-directional or zero flow is possible, the mass flow rates through the vent corresponding to $\Delta p = 0$ are seen to be identically zero. However, for the unstable cross-vent density configurations of Cases 29 and 30, the vent flow algorithm is seen to respond to the exchange-flow phenomenon. In particular, there is a non-zero vent flow exchange between the top and bottom spaces whenever $|\Delta p| < \Delta p_{FLOOD}$, where Δp_{FLOOD} is defined in Eq. (19) of the Appendix.

ACKNOWLEGEMENTS

The author acknowleges gratefully the Naval Research Laboratory which sponsored this work under the technical management of Dr. Patricia A. Tatem and with the support of Ms. Jean L. Bailey.

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NOMENCLATURE

$\dot{M}_{VENT,I}$; I = 1 to 2

Mass flow rate of the vent flow component entering space I

p_{DATUM}

Datum absolute pressure

p_{HIGH}

Maximum of (p_1, p_2)

p_{LOW}

Minimum of (p_1, p_2)

$p_{REF,I}$; I = 1 or 2

Absolute pressure in space I at the reference elevation $y_{REF,I}$

p_1 $[p_2]$

Absolute hydrostatic pressure in the top [bottom] space at the elevation of the vent

y_C, y_L, y_R for space I

$y_{CEIL,I}$, $y_{LAYER,I}$, and $y_{REF,I}$, respectively.

$y_{CEIL,I}$ $[y_{REF,I}]$; I = 1 or 2

If space I is an inside room: elevation of the ceiling [floor] of room I above the datum elevation; if space I is an "outside room": $y_{CEIL,I}$ and $y_{REF,I}$ are both identical and equal to the reference elevation of space I above the datum elevation, i.e., $y_{CEIL,I} \equiv y_{REF,I}$

$y_{LAYER,I}$; I = 1 or 2

If space I is an inside room: elevation of the upper/lower layer interface in room I above the datum elevation; if space I is an "outside room": $y_{LAYER,I} \equiv y_{REF,I}$

y_{VENT}

Elevation of the vent above the datum elevation

Δp

$p_2 - p_1$

Δp_{FLOOD}

Minimum value of $|\Delta p|$, in cases of unstable cross-vent density configurations, leading to unidirectional vent flow; Eq. (19) of Appendix

$\delta p_{REF,I}$; I = 1 or 2

Pressure at the reference elevation, $y_{REF,I}$, in space I above the datum absolute pressure, p_{DATUM}; if space I is an inside room, then $\delta p_{REF,I}$ and $y_{REF,I}$ correspond to the pressure and elevation, respectively, within the room and at the floor

$\rho_{L,I}$ [$\rho_{U,I}$]; I = 1 or 2

If space I is an inside room: density of the lower [upper] layer in room I if the volume of the lower [upper] layer is non-zero (if the lower [upper] layer volume is zero then the $\rho_{L,I}$ [$\rho_{U,I}$] value is not used in the calculation); if space I is an "outside room": $\rho_{L,I}$ is the uniform density there and $\rho_{U,I} \equiv \rho_{L,I}$

TABLE 1: Configurations/Environments Used to Test the VENTCF Subroutine

$\rho_1 = 1.00\text{kg/m}^3 > \rho_2 = 0.50\text{kg/m}^3 > \rho_3 = 0.25\text{kg/m}^3$
$y_1 = 0.0\text{m} < y_2 = 1.5\text{m} < y_3 = 3.0\text{m} < y_4 = 4.5\text{m} < y_5 = 6.0\text{m}$
$p_{DATUM} = 1.01325(10^5)\text{pa}$

CASES 1-54: SPACE 1 (TOP SPACE) IS INSIDE ROOM, SPACE 2 (BOTTOM SPACE) IS INSIDE ROOM - APPENDIX: FIGURE 1a

CASE NO.	SPACE 1	SPACE 2		
	Lower Layer $y_R=y_3$ $y_L=y_5$ $y_C=y_5$	Lower Layer $y_R=y_1$ $y_L=y_3$ $y_C=y_3$		
1			$\rho_{L,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
2			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
3			$\rho_{L,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
4			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
5	*		$\rho_{L,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
6	*	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		Two Layers $y_R=y_1$ $y_L=y_2$ $y_C=y_3$		
7			$\rho_{L,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
8			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
9			$\rho_{L,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
10			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
11	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
12	*	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		Upper Layer $y_R=y_1$ $y_L=y_1$ $y_C=y_3$		
13			$\rho_{L,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
14			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
15			$\rho_{L,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
16			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
17	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
18	* ↓	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$

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* Unstable cross-vent density configuration

TABLE 1: (Cont'd) Configurations/Environments Used to Test the VENTCF Subroutine

$\rho_1 = 1.00 kg/m^3 > \rho_2 = 0.50 kg/m^3 > \rho_3 = 0.25 kg/m^3$
$y_1 = 0.0 m < y_2 = 1.5 m < y_3 = 3.0 m < y_4 = 4.5 m < y_5 = 6.0 m$
$p_{DATUM} = 1.01325(10^5) pa$

CASES 1-54: (CONT'D) SPACE 1 (TOP SPACE) IS INSIDE ROOM, SPACE 2 (BOTTOM SPACE) IS INSIDE ROOM - APPENDIX: FIGURE 1a

CASE NO.	SPACE 1	SPACE 2		
19	Two Layer $y_R=y_3$ $y_L=y_4$ $y_C=y_5$	Lower Layer $y_R=y_1$ $y_L=y_3$ $y_C=y_3$	$\rho_{L,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
20			"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
21			$\rho_{L,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
22			"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
23	*		$\rho_{L,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
24	*		"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
25		Two Layer $y_R=y_1$ $y_L=y_2$ $y_C=y_3$	$\rho_{L,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
26			"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
27			$\rho_{L,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
28			"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
29	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
30	*		"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
31		Upper Layer $y_R=y_1$ $y_L=y_1$ $y_C=y_3$	$\rho_{L,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
32			"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
33			$\rho_{L,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
34			"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
35	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0.$, $-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
36	*		"	$\delta p_{REF,2}=0.$, $-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$

TABLE 1: Configurations/Environments Used to Test the VENTCF Subroutine (Cont'd)

$\rho_1 = 1.00 kg/m^3 > \rho_2 = 0.50 kg/m^3 > \rho_3 = 0.25 kg/m^3$
$y_1 = 0.0m < y_2 = 1.5m < y_3 = 3.0m < y_4 = 4.5m < y_5 = 6.0m$
$p_{DATUM} = 1.01325(10^5) pa$

CASES 1-54: (CONT'D) SPACE 1 (TOP SPACE) IS INSIDE ROOM, SPACE 2 (BOTTOM SPACE) IS INSIDE ROOM - APPENDIX: FIGURE 1a

CASE NO.	SPACE 1	SPACE 2		
37	Upper Layer $y_R=y_3$ $y_L=y_3$ $y_C=y_5$	Lower Layer $y_R=y_1$ $y_L=y_3$ $y_C=y_3$	$\rho_{U,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
38			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
39			$\rho_{U,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
40			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
41	*		$\rho_{U,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
42	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
43		Two Layer $y_R=y_1$ $y_L=y_2$ $y_C=y_3$	$\rho_{U,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
44			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
45			$\rho_{U,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
46			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
47	*		$\rho_{U,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
48	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
49		Upper Layer $y_R=y_1$ $y_L=y_1$ $y_C=y_3$	$\rho_{U,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
50			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
51			$\rho_{U,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
52			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
53	*		$\rho_{U,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
54	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$

TABLE 1: Configurations/Environments Used to Test the VENTCF Subroutine (Cont'd)

$\rho_1 = 1.00\text{kg/m}^3 > \rho_2 = 0.50\text{kg/m}^3 > \rho_3 = 0.25\text{kg/m}^3$
$y_1 = 0.0\text{m} < y_2 = 1.5\text{m} < y_3 = 3.0\text{m} < y_4 = 4.5\text{m} < y_5 = 6.0\text{m}$
$p_{DATUM} = 1.01325(10^5)\text{pa}$

CASES 55-108: SPACE 1 (TOP SPACE) IS OUTSIDE SPACE, SPACE 2 (BOTTOM SPACE) IS INSIDE ROOM - APPENDIX: FIGURE 1b

CASE NO.	SPACE 1	SPACE 2		
	All One Layer $y_R=y_4$ $y_L=y_4$ $y_C=y_4$	Lower Layer $y_R=y_1$ $y_L=y_3$ $y_C=y_3$		
55			$\rho_{L,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
56			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
57			$\rho_{L,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
58			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
59	*		$\rho_{L,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
60	*	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		Two Layers $y_R=y_1$ $y_L=y_2$ $y_C=y_3$		
61			$\rho_{L,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
62			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
63			$\rho_{L,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
64			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
65	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
66	*	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		Upper Layer $y_R=y_1$ $y_L=y_1$ $y_C=y_3$		
67			$\rho_{L,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
68			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
69			$\rho_{L,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
70			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
71	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
72	* ↓	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$

TABLE 1: Configurations/Environments Used to Test the VENTCF Subroutine
(Cont'd)

$\rho_1 = 1.00 kg/m^3 > \rho_2 = 0.50 kg/m^3 > \rho_3 = 0.25 kg/m^3$
$y_1 = 0.0m < y_2 = 1.5m < y_3 = 3.0m < y_4 = 4.5m < y_5 = 6.0m$
$p_{DATUM} = 1.01325(10^5)pa$

CASES 55-108: SPACE 1 (TOP SPACE) IS OUTSIDE SPACE, SPACE 2 (BOTTOM SPACE)
(CONT'D) IS INSIDE ROOM - APPENDIX: FIGURE 1b

CASE NO.	SPACE 1	SPACE 2		
	All One Layer $y_R=y_3$ $y_L=y_3$ $y_C=y_3$	Lower Layer $y_R=y_1$ $y_L=y_3$ $y_C=y_3$		
73			$\rho_{L,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
74			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
75			$\rho_{L,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
76			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
77	*		$\rho_{L,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
78	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		Two Layer $y_R=y_1$ $y_L=y_2$ $y_C=y_3$		
79			$\rho_{L,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
80			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
81			$\rho_{L,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
82			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
83	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
84	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		Upper Layer $y_R=y_1$ $y_L=y_1$ $y_C=y_3$		
85			$\rho_{L,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
86			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
87			$\rho_{L,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
88			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
89	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
90	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$

TABLE 1: Configurations/Environments Used to Test the VENTCF Subroutine
(Cont'd)

$\rho_1 = 1.00kg/m^3 > \rho_2 = 0.50kg/m^3 > \rho_3 = 0.25kg/m^3$
$y_1 = 0.0m < y_2 = 1.5m < y_3 = 3.0m < y_4 = 4.5m < y_5 = 6.0m$
$p_{DATUM} = 1.01325(10^5)pa$

CASES 55-108: SPACE 1 (TOP SPACE) IS OUTSIDE SPACE, SPACE 2 (BOTTOM SPACE)
(CONT'D) IS INSIDE ROOM - APPENDIX: FIGURE 1b

CASE NO.	SPACE 1	SPACE 2		
	All One Layer $y_R=y_2$ $y_L=y_2$ $y_C=y_2$	Lower Layer $y_R=y_1$ $y_L=y_3$ $y_C=y_3$		
91			$\rho_{U,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
92			"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
93			$\rho_{U,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
94			"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
95	*		$\rho_{U,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
96	*	↓	"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		Two Layer $y_R=y_1$ $y_L=y_2$ $y_C=y_3$		
97			$\rho_{U,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
98			"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
99			$\rho_{U,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
100			"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
101	*		$\rho_{U,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
102	*	↓	"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		Upper Layer $y_R=y_1$ $y_L=y_1$ $y_C=y_3$		
103			$\rho_{U,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
104			"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
105			$\rho_{U,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
106			"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
107	*		$\rho_{U,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0.,-p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
108	* ↓	↓	"	$\delta p_{REF,2}=0.,-p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$

TABLE 1: (Cont'd) Configurations/Environments Used to Test the VENTCF Subroutine

$\rho_1 = 1.00 kg/m^3 > \rho_2 = 0.50 kg/m^3 > \rho_3 = 0.25 kg/m^3$
$y_1 = 0.0m < y_2 = 1.5m < y_3 = 3.0m < y_4 = 4.5m < y_5 = 6.0m$
$p_{DATUM} = 1.01325(10^5)pa$

CASES 109-162: SPACE 1 (TOP SPACE) IS INSIDE ROOM, SPACE 2 (BOTTOM SPACE) IS OUTSIDE SPACE - APPENDIX: FIGURE 1c

CASE NO.	SPACE 1	SPACE 2		
	Lower Layer $y_R=y_3$ $y_L=y_5$ $y_C=y_5$	All One Layer $y_R=y_4$ $y_L=y_4$ $y_C=y_4$		
109			$\rho_{L,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
110			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
111			$\rho_{L,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
112			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
113	*		$\rho_{L,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
114	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		$y_R=y_3$ $y_L=y_3$ $y_C=y_3$		
115			$\rho_{L,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
116			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
117			$\rho_{L,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
118			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
119	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
120	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		$y_R=y_2$ $y_L=y_2$ $y_C=y_2$		
121			$\rho_{L,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
122			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
123			$\rho_{L,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
124			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
125	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
126	*		"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$

TABLE 1: Configurations/Environments Used to Test the VENTCF Subroutine (Cont'd)

$\rho_1 = 1.00\text{kg/m}^3 > \rho_2 = 0.50\text{kg/m}^3 > \rho_3 = 0.25\text{kg/m}^3$
$y_1 = 0.0\text{m} < y_2 = 1.5\text{m} < y_3 = 3.0\text{m} < y_4 = 4.5\text{m} < y_5 = 6.0\text{m}$
$p_{DATUM} = 1.01325(10^5)\text{pa}$

CASES 109-162: (CONT'D) SPACE 1 (TOP SPACE) IS INSIDE ROOM, SPACE 2 (BOTTOM SPACE) IS OUTSIDE SPACE - APPENDIX: FIGURE 1c

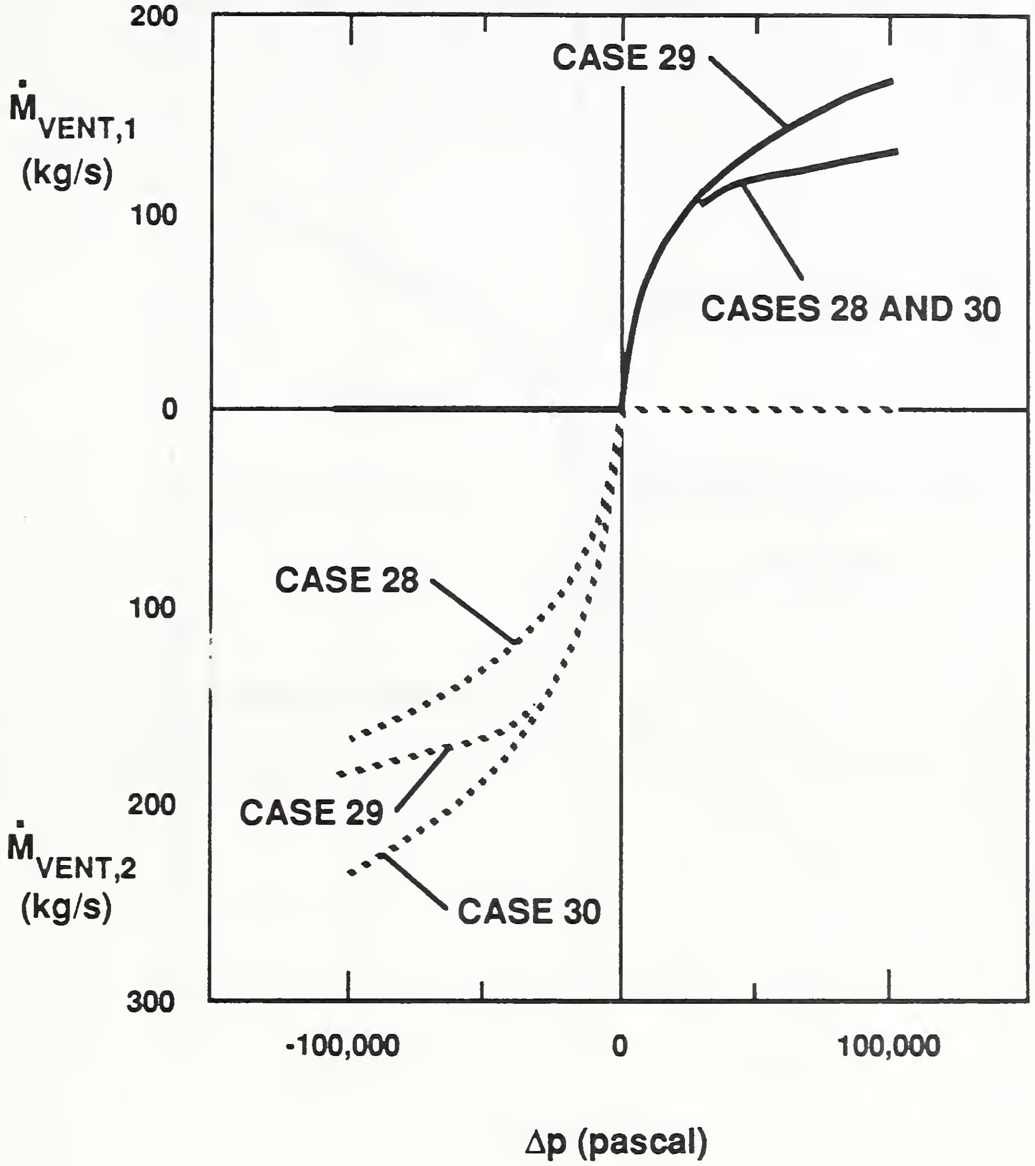
CASE NO.	SPACE 1	SPACE 2		
	Two Layer $y_R=y_3$ $y_L=y_4$ $y_C=y_5$	All One Layer $y_R=y_4$ $y_L=y_4$ $y_C=y_4$		
127			$\rho_{L,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
128			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
129			$\rho_{L,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
130			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
131	*		$\rho_{L,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
132	*	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		$y_R=y_3$ $y_L=y_3$ $y_C=y_3$		
133			$\rho_{L,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
134			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
135			$\rho_{L,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
136			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
137	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
138	*	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		$y_R=y_2$ $y_L=y_2$ $y_C=y_2$		
139			$\rho_{L,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
140			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
141			$\rho_{L,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
142			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
143	*		$\rho_{L,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
144	* ↓	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$

TABLE 1: Configurations/Environments Used to Test the VENTCF Subroutine
(Cont'd)

$\rho_1 = 1.00\text{kg/m}^3 > \rho_2 = 0.50\text{kg/m}^3 > \rho_3 = 0.25\text{kg/m}^3$
$y_1 = 0.0\text{m} < y_2 = 1.5\text{m} < y_3 = 3.0\text{m} < y_4 = 4.5\text{m} < y_5 = 6.0\text{m}$
$p_{DATUM} = 1.01325(10^5)\text{pa}$

CASES 109-162: SPACE 1 (TOP SPACE) IS INSIDE ROOM, SPACE 2 (BOTTOM SPACE)
(CONT'D) IS OUTSIDE SPACE - APPENDIX: FIGURE 1c

CASE NO.	SPACE 1	SPACE 2		
	Upper Layer	All One Layer		
	$y_R=y_3$ $y_L=y_3$ $y_C=y_5$	$y_R=y_4$ $y_L=y_4$ $y_C=y_4$		
145			$\rho_{U,1}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
146			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
147			$\rho_{U,1}=\rho_1=\rho_{L,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
148			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
149	*		$\rho_{U,1}=\rho_1>\rho_{L,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
150	*	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		$y_R=y_3$ $y_L=y_3$ $y_C=y_3$		
151			$\rho_{U,1}=\rho_3<\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
152			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
153			$\rho_{U,1}=\rho_2=\rho_{U,2}<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
154			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
155	*		$\rho_{U,1}=\rho_1>\rho_{U,2}=\rho_2<\rho_{L,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
156	*	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
		$y_R=y_2$ $y_L=y_2$ $y_C=y_2$		
157			$\rho_{U,1}=\rho_2<\rho_{U,2}=\rho_1$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
158			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
159			$\rho_{U,1}=\rho_1=\rho_{U,2}$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
160			"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$
161	*		$\rho_{U,1}=\rho_1>\rho_{U,2}=\rho_2$	$\delta p_{REF,1}=0., -p_{DATUM}<\delta p_{REF,2}\le p_{DATUM}$
162	* ↓	↓	"	$\delta p_{REF,2}=0., -p_{DATUM}<\delta p_{REF,1}\le p_{DATUM}$



igure 1. Plots of the calculated mass flow rate to upper space 1, $\dot{M}_{VENT,1}$, and to lower space 2, $\dot{M}_{VENT,2}$, as functions of the computed (coarse-scale) cross-vent pressure difference, Δp, for Cases 28, 29, and 30 (see Table 1).

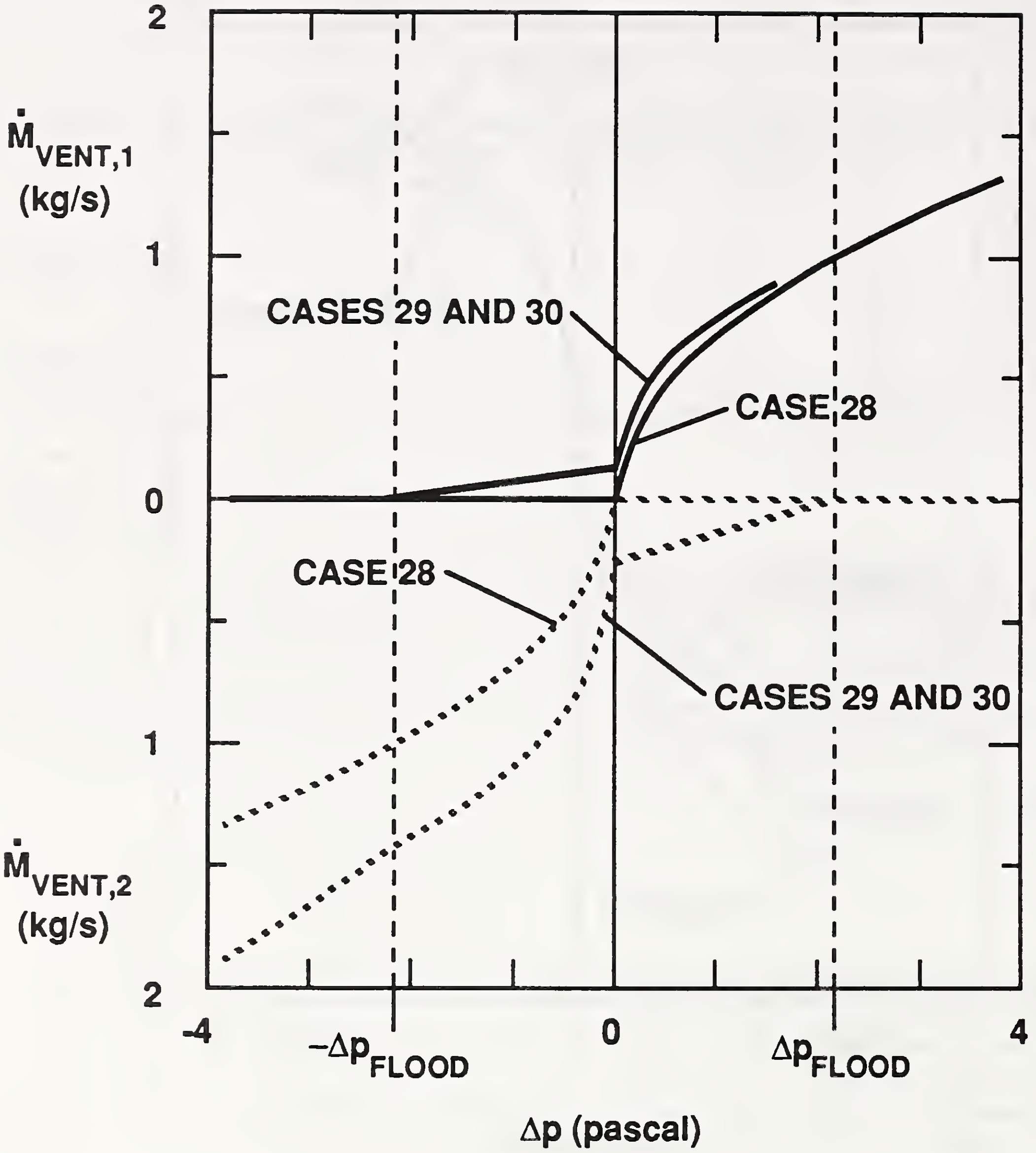


Figure 2. Plots of the calculated mass flow rate to upper space 1, $\dot{M}_{VENT,1}$, and to lower space 2, $\dot{M}_{VENT,2}$, as functions of the computed (fine-scale) cross-vent pressure difference, Δp, for Cases 28, 29, and 30 (see Table 1).

APPENDIX

VENTCF - Calculation of the Flow Through a Horizontal Ceiling/Floor Vent Connecting Two Spaces

VENTCF - Calculation of the Flow Through a Horizontal Ceiling/Floor Vent Connecting Two Spaces

DESCRIPTION

Consider an instant of time during the simulation of a multi-room compartment fire environment. This algorithm can be used to calculate the flow of mass, enthalpy, oxygen, and other products of combustion through a horizontal vent located in a ceiling/floor segment common to any two inside rooms of the facility or between an inside room and the outside environment local to the vent.

Depicted in Figure 1a is the vent and the two spaces when they are both inside rooms of a multi-room facility. Figures 1b and 1c depict the situation when the two spaces involve one inside room of the facility and one outside space, either above or below the room, in which is simulated the outside environment local to the vent.

As in Figure 1, designate the top space as space 1 and the bottom space as space 2. It is assumed that the temperature, density, concentration of oxygen and of other products of combustion of interest in the upper and lower layer of each inside room and in the environment local to the vent of an outside space are specified. Also specified in each inside room are: the elevation above a datum elevation of the floor, and the upper-layer/lower-layer interface; the pressure at the floor of each room above a specified datum pressure; and the datum absolute pressure there. Specified in an outside space are: a reference elevation above the datum elevation, and the pressure at this reference elevation above the specified datum pressure.

The calculation of flow through the vent is based on the model of reference [1] which takes into account considerations of flow due to a cross-vent pressure difference and, when appropriate, of flow induced through the vent when existing fluid configurations are unstable, i.e., when a relatively cool, dense gas in the upper space overlays a less dense gas in the lower space. Whereas a non-zero cross-vent pressure difference always tends to drive a unidirectional flow through the vent, from the higher- to the lower-pressure side, flow induced by an unstable fluid density configuration tends to lead to an exchange-type of flow, with fluid in the lower space rising into the upper space and flow from the upper space dropping into the lower space. As a result, the flow through the vent can be unidirectional, into the upper or lower space, or it can involve a complex two-component flow, whereby flow is drawn simultaneously from the bottom to the top space and from the top to the bottom space.

The geometry and the conditions local to the vent which determine the characteristics of the vent flow are depicted in Figure 2. These include: the densities, ρ_1 and ρ_2, and the hydrostatic pressures, p_1 and p_2, at the elevation, but away from the immediate vicinity of the vent in the upper and lower spaces, respectively, and the area, A_v, and shape of the vent. Regarding the shape, at the present time results for horizontal vent flows are only available for circular or square vents. Other properties local to the vent and indicated in Figure 2 are T_1 and T_2, the absolute temperatures, $c_{O2,1}$ and $c_{O2,2}$, the concentrations of oxygen, and $c_{K,1}$ and $c_{K,2}$, K = 2 to N_{PROD}, the concentrations of a product of combustion K.

In the present algorithm, the calculation of the vent flow is based on the previously developed theory presented in reference [1]. When the scenario involves an unstable density configuration, it is determined there that an exchange-type of flow occurs if the magnitude of the cross-vent pressure difference is less than that of a characteristic value, Δp_{FLOOD}, a specified function of cross-vent density difference and size and shape of the vent.

When the vent flow is unidirectional the model of [1] uses the incompressible orifice-flow-type of flow rate calculation. This is the method presented, e.g., in reference [2] and used traditionally in most zone-type compartment fire models to calculate the rate of flow through vents of vertical orientation. In order to be able to treat fire scenarios at times when vent flows are driven by arbitrarily high cross-vent pressure differences, i.e., when compressibility effects begin to be significant, the model of [1] has been modified here to include the ideas introduced in reference [3] and implemented in the VENTHP algorithm/subroutine of reference [4]. Such high cross-vent pressure differences could occur, for example, in fire scenarios involving flows through cracks in otherwise hermetically-sealed fire compartments.

The VENTCF subroutine has been subjected to extensive parametric testing in a "stand-alone" mode. This is described in reference [5].

OUTPUT

$c_{O2,1}$ [$c_{O2,2}$]

Concentration of oxygen in the top [bottom] space at the elevation of the vent. [(kg of oxygen)/(kg of layer)]

$c_{K,1}$ [$c_{K,2}$]

Concentration of product K in the top [bottom] space at the elevation of the vent. [(unit of product K)/(kg of layer)]

$c_{VENT,O2,I}$; I = 1 or 2

Concentration of oxygen in the component of the vent flow entering space I, provided such vent flow component is non-zero, i.e., provided $\dot{M}_{VENT,I}$. is non-zero. [(kg of oxygen)/(kg of vent flow)]

$c_{VENT,K,I}$; I = 1 or 2; K = 2 to NPROD

Concentration of product of combustion K in the component of the vent flow entering space I, provided such vent flow component is nonzero, i.e., provided $\dot{M}_{VENT,I}$. is non-zero. [(unit of product)/(kg of vent flow)]

$\dot{M}_{U,I}$ [$\dot{M}_{L,I}$]; I = 1 or 2

If space I is an inside room: Rate at which mass is added to the upper [lower] layer of room I due to the vent flow component which enters the other space. Note that this will always be negative, since the layer which supplies the material flowing to the other space will always have mass extracted from it. [W]

If space I is an "outside room": $\dot{M}_{U,I}$ is the rate at which mass is added to space I due to the vent flow component which enters the other space (i.e., the inside room). Note that this will always be negative, since an outside space which supplies material flowing through the vent to an adjacent space will always have mass extracted from it. $\dot{M}_{L,I}$ is identical to $\dot{M}_{U,I}$. [W]

$\dot{M}_{VENT,I}$; I = 1 to 2

Mass flow rate of the vent flow component entering space I. [kg/s]

$\dot{P}_{O2,L,I}$ [$\dot{P}_{O2,U,I}$]; I = 1 or 2

If space I is an inside room: Rate at which oxygen is added to the upper [lower] layer of room I due to the vent flow component which enters the other space. Note that this will always be negative, since the layer which supplies the material flowing through the vent to the other space will always have its convected oxygen extracted from it. [(kg of O_2)/s]

If space I is an "outside room": $\dot{P}_{O2,U,I}$ is the rate at which oxygen is added to space I due to the vent flow component which enters the other space (i.e., the inside room). Note that this will always be negative, since an outside space which supplies material flowing through the vent to an adjacent space will always have its convected oxygen extracted from it. $\dot{P}_{O2,L,I}$ is identical to $\dot{P}_{O2,U,I}$. [(kg of O_2)/s]

$\dot{P}_{O2,VENT,I}$; I = 1 to 2

Mass flow rate of oxygen of the vent flow component entering space I. [(kg of oxygen)/s]

$\dot{P}_{K,L,I}$ [$\dot{P}_{K,U,I}$]; K = 2 to N_{PROD}; I = 1 or 2

If space I is an inside room: Rate at which product of combustion K is <u>added</u> to the upper [lower] layer of room I due to the vent flow component which enters the other space. Note that this will <u>always be negative</u> since the layer which supplies the material flowing through the vent to the other space will always have its convected product of combustion K <u>extracted</u> from it. [(unit of product K)/s]

If space I is an "outside room": $\dot{P}_{K,U,I}$ is the rate at which product of combustion K is <u>added</u> to space I due to the vent flow component which enters the other space (i.e., the inside room). Note that this will <u>always be negative</u>, since an outside space which supplies material flowing through the vent to an adjacent space will always have the convected product of combustion K <u>extracted</u> from it. $\dot{P}_{K,L,I}$ is identical to $\dot{P}_{K,U,I}$. [(unit of product K)/s]

$\dot{P}_{K,VENT,I}$; I = 1 to 2; K = 2 to N_{PROD}

Flow rate of product of combustion K in the vent flow component entering space I. [(unit of product K)/s]

p_1 [p_2]

Absolute hydrostatic pressure in the top [bottom] space at the elevation of the vent. [$Pa = kg/(m \cdot s^2)$]

$\dot{Q}_{U,I}$ [$\dot{Q}_{L,I}$]; I = 1 or 2

If space I is an inside room: Rate at which enthalpy <u>added</u> to the upper [lower] layer of room I due to the vent flow component which enters the other space. Note that this will <u>always be negative</u>, since the layer which supplies the material which flows to the other space will always have its convected enthalpy <u>extracted</u> from it. The enthalpy is based on the absolute temperature of the flow, $T_{VENT,I}$. [W]

If space I is an "outside room": $\dot{Q}_{U,I}$ is the rate at which enthalpy is <u>added</u> to space I due to the vent flow component which enters the other space (i.e., the inside room). Note that this will <u>always be negative</u>, since an outside space which supplies material which flows through the vent to an adjacent space will always have its convected enthalpy <u>extracted</u> from it. The enthalpy is based on the absolute temperature of the flow, $T_{U,I}$. $\dot{Q}_{L,I}$ is identical to $\dot{Q}_{U,I}$. [W]

$\dot{Q}_{VENT,I}$; I = 1 to 2

Total enthalpy flow rate in the vent flow component entering space I. This is based on the absolute temperature of the flow, $T_{VENT,I}$. [W]

T_1 [T_2]

Absolute temperature in the top [bottom] space at the elevation of the vent. [K]

$T_{VENT,I}$; I = 1 to 2

Absolute temperature of the vent flow component entering space I, provided such vent flow component is non-zero. [K]

Δp

$p_2 - p_1$, i.e., pressure in the bottom space at the elevation of the vent - pressure in the top space at the elevation of the vent. [Pa = $kg/(m \cdot s^2)$]

ρ_1 [ρ_2]

Density in the top [bottom] space at the elevation of the vent. [kg/m**3]

$\rho_{VENT,I}$; I = 1 to 2

Density of the vent flow component entering space I, provided such vent flow component is nonzero. [kg/m^3]

INPUT

A_V

Area of the vent [m^2].

$c_{L,K,I}$ [$c_{U,K,I}$]; K = 2 to N_{PROD}; I = 1 or 2

If space I is an inside room: Concentration of product of combustion K in lower [upper] layer of room I if the volume of the lower [upper] layer is non-zero (if the lower [upper] layer volume is zero then the $c_{L,K,I}$ [$c_{U,K,I}$] value is not used in the calculation). [(unit of product K)/(kg of layer)]

If space I is an "outside room": $c_{L,K,I}$ is the uniform concentration throughout the space of product of combustion K; $c_{U,K,I}$ is specified as being identical to $c_{L,K,I}$. [(unit of product K)/(kg of local atmosphere)]

$c_{L,O2,I}$ [$c_{U,O2,I}$]; I = 1 or 2

If space I is an inside room: Concentration of oxygen in lower [upper] layer of room I if the volume of the lower [upper] layer is non-zero (if the lower [upper] layer volume is zero then the $c_{L,O2,I}$ [$c_{U,O2,I}$] value is not used in the calculation). [(kg of oxygen)/(kg of layer)]

If space I is an "outside room": $c_{L,O2,I}$ is the uniform concentration throughout the space of oxygen; $c_{U,O2,I}$ is specified as being identical to $c_{L,O2,I}$. [(kg of oxygen)/(kg of local atmosphere)]

C_p

Specific heat at constant pressure of the vent flow. [W·s/(kg·K)] (suggest 10^3 W·s/(kg·K) for air as default)

D

Characteristic dimension of the vent: the diameter of a circular vent and the length of a side of a square vent. [m]

N_{PMAX}

Maximum allowed number of products of combustion.

N_{PROD}

Number of products of combustion, including oxygen, being tracked in the simulation.

N_{SHAPE}

Number associated with the shape of the horizontal vent (the present algorithm is based on results for circular and square vents)

$$N_{SHAPE} = \begin{cases} 1 & \text{for a circular vent} \\ 2 & \text{for a square vent} \end{cases}$$

p_{DATUM}

Datum absolute pressure. [Pa = kg/(m·s^2)]

$T_{L,I}$ [$T_{U,I}$]; I = 1 or 2

If space I is an inside room: Absolute temperature of the lower [upper] layer in room I if the volume of the lower [upper] layer is non-zero (if the lower [upper] layer volume is zero then the $T_{L,I}$ [$T_{U,I}$] value is not used in the calculation). [K]

If space I is an "outside room": $T_{L,I}$ is the uniform absolute temperature there, taken to be the temperature at the reference elevation, $y_{REF,I}$; $T_{U,I}$ is specified as being identical to $T_{L,I}$. [K]

$y_{CEIL,I}$ [$y_{REF,I}$]

If space I is an inside room: Elevation of the ceiling [floor] of room I above the datum elevation. [m]

If space I is an "outside room": $y_{CEIL,I}$ and $y_{REF,I}$ are both identical and equal to the reference elevation of space I above the datum elevation, i.e., the specification must satisfy $y_{CEIL,I} \equiv y_{REF,I}$. The latter identity, which will never be satisfied for an inside room, is a characteristic of the input data used to distinguish an inside room from an "outside room." [m]

$y_{LAYER,I}$; I = 1 or 2

If space I is an inside room: Elevation of the upper/lower layer interface in room I above the datum elevation. [m]

If space I is an "outside room": $y_{LAYER,I}$ is specified as being identical to $y_{REF,I}$. [m]

y_{VENT}

Elevation of the vent above the datum elevation. Note that y_{VENT} must be identical to either $y_{CEIL,I}$ or $y_{REF,I}$ for each of the one or two inside rooms involved in the calculation. [m]

$\delta p_{REF,I}$; I = 1 or 2

Pressure at the reference elevation, $y_{REF,I}$, in space I above the datum absolute pressure, p_{DATUM}. If space I is an inside room, then $\delta p_{REF,I}$ and $y_{REF,I}$ must correspond to the pressure and elevation, respectively, within the room and at the floor. [Pa = kg/(m·s^2)]

ϵ_p

Error tolerance for $\delta p_{REF,I}$. If $p_{ERROR,I}$ is defined as the uncertainty in $\delta p_{REF,I}$, I = 1 or 2, then $p_{ERROR,I}$ satisfies

$$|p_{ERROR,I}| < \epsilon_p p_0 + |\delta p_{REF,I}| \epsilon_p$$

where p_0 = 1.0 Pa. The first term is based on an absolute error tolerance and dominates the above error bound when $|\delta p_{REF,I}|$ is less than 1.0 Pa. The second term is a relative error tolerance and dominates when $|\delta p_{REF,I}|$ is greater than 1.0 Pa. ϵ_p should be chosen to be consistent with the tolerance specified for the computation of $\delta p_{REF,I}$ terms in the overall compartment fire model computer code which uses this algorithm.

$\rho_{L,I}$ $[\rho_{U,I}]$; I = 1 or 2

If space I is an inside room: Density of the lower [upper] layer in room I if the volume of the lower [upper] layer is non-zero (if the lower [upper] layer volume is zero then the $\rho_{L,I}$ $[\rho_{U,I}]$ value is not used in the calculation). [kg/m^3]

If space I is an "outside room": $\rho_{L,I}$ is the uniform density there; $\rho_{U,I}$ is specified as being identical to $\rho_{L,I}$. [kg/m^3]

CALCULATION

1. Calculate p_I for I = 1 and 2 , and then Δp (the p_I calculation follows the DELP algorithm/subroutine of reference [6]):

$$p_I = \delta p_{REF,I} + \delta p_I + p_{DATUM} \tag{1}$$

$$\Delta p = p_2 - p_1 = (\delta p_{REF,2} - \delta p_{REF,1}) + (\delta p_2 - \delta p_1) \tag{2}$$

where

if $y_{REF,I} \leq y_{VENT} \leq y_{LAYER,I}$ then:

$$\delta p_I = - \rho_{L,I} g(y_{VENT} - y_{REF,I})$$

else:

$$\delta p_I = - \rho_{L,I} g(y_{LAYER,I} - y_{REF,I}) \tag{3}$$

and where g, the acceleration of gravity, is 9.8 m/s^2.

2. Calculate ρ_I, T_I, $c_{O2,I}$, and the $c_{K,I}$, K = 2 to N_{PROD}, for I = 1 and 2, and then $\Delta\rho$:

if $\{[(y_{VENT} = y_{REF,I})$ and $(y_{LAYER,I} = y_{REF,I})]$ or

$[(y_{VENT} = y_{CEIL,I})$ and $(y_{LAYER,I} < y_{CEIL,I})]\}$ then:

$\rho_I = \rho_{U,I}$, $T_I = T_{U,I}$, $c_{O2,I} = c_{U,O2,I}$, and $c_{K,I} = c_{U,K,I}$

else:

$\rho_I = \rho_{L,I}$, $T_I = T_{L,I}$, $c_{O2,I} = c_{L,O2,I}$, and $c_{K,I} = c_{L,K,I}$

(4)

$$\Delta\rho = \rho_1 - \rho_2 \qquad (5)$$

3. Define $\dot{V}_{ST,I}$ as the volume rate of flow through the vent into space I that is predicted with a "standard," unidirectional-flow-type calculation, where arbitrarily high cross-vent pressures are allowed. Here, the calculation follows the model of reference [3] as implemented in the VENTHP algorithm/subroutine of reference [4]. Calculate $\dot{V}_{ST,I}$, I = 1 and 2:

If $\Delta p = 0$ then:

$$\dot{V}_{ST,1} = \dot{V}_{ST,2} = 0 \qquad (6)$$

If $\Delta p > 0$ or $\Delta p < 0$ then:

Define and compute ρ, ϵ, and x:

If $\Delta p > 0$, i.e., "standard" flow from (lower) space 2 to (upper) space 1, then:

$$\rho = \rho_2; \quad \epsilon = \Delta p/p_2 \qquad (7)$$

If $\Delta p < 0$, i.e., "standard" flow from (upper) space 1 to (lower) space 2, then:

$$\rho = \rho_1; \quad \epsilon = -\Delta p/p_1 \qquad (8)$$

$$x = 1 - \epsilon \qquad (9)$$

Compute C(x), the vent flow coeffient, and w(x):

$$C(x) = 0.85 - 0.17x = 0.68 + 0.17\epsilon \qquad (10)$$

$$w(x) = \begin{cases} 1 - [3/(4\gamma)]\epsilon & \text{if } 0 < \epsilon \leq 10^{-5} \\ f(x)/[2\epsilon]^{1/2} & \text{if } 1 \geq \epsilon > 10^{-5} \end{cases} \qquad (11)$$

where

$$f(x) = \begin{cases} \{[2\gamma/(\gamma - 1)]x^{2/\gamma}[1 - x^{(\gamma - 1)/\gamma}]\}^{1/2} \\ \qquad \text{if } \epsilon < 1 - [2/(\gamma + 1)]^{\gamma/(\gamma - 1)} \\ \{\gamma[2/(\gamma + 1)]^{(\gamma + 1)/(\gamma - 1)}\}^{1/2} \\ \qquad \text{if } \epsilon \geq 1 - [2/(\gamma + 1)]^{\gamma/(\gamma - 1)} \end{cases} \qquad (12)$$

and where γ, the ratio of specific heats of the vent flow gas, is taken to be that of air, 1.40.

Define and compute $\Delta p_{CUT}^{1/2}$:

$$\Delta p_{CUT}^{1/2} = [\epsilon_p \cdot \mathrm{MAX}(1.0\ \text{pascal}, |\delta p_{REF,1}|, |\delta p_{REF,2}|)]^{1/2} \qquad (13)$$

Define and compute F_{NOISE}, a numerical damping factor:

$$F_{NOISE} = 1.0 - \exp(-|\Delta p|^{1/2}/\Delta p_{CUT}^{1/2}) \qquad (14)$$

Compute $\dot{V}$, the "standard" volume flow rate from the high to low pressure space, and $\dot{V}_{ST,I}$, I = 1 and 2:

$$\dot{V} = F_{NOISE} C(x) w(x) (2/\rho)^{1/2} A_V |\Delta p|^{1/2} \qquad (15)$$

$$\dot{V}_{ST,1} = \dot{V},\ \dot{V}_{ST,2} = 0 \quad \text{if } \Delta p > 0 \qquad (16)$$

$$\dot{V}_{ST,2} = \dot{V},\ \dot{V}_{ST,1} = 0 \quad \text{if } \Delta p < 0 \qquad (17)$$

Note in Eqs. (7) and (8) that $\epsilon \to 0$, i.e., $x \to 1$, corresponds to the incompressible limit where $C \to 0.68$ in Eq. (10) according to the recommendation of reference [2].

The term F_{NOISE} of Eq. (14) is designed to damp out the numerical noise (error) in the calculated value for Δp that would otherwise be dominant in Eq. (15) when Δp is small relative to the maximum of 1.0 pascal and the calculated reference pressures, $\delta p_{REF,1}$, $\delta p_{REF,2}$. The term Δp_{CUT} of Eq. (13) is an estimate of how small the maximum of $|\Delta p|$ must be to retain a few digits of accuracy in the calculation of Δp. When the calculated value of $|\Delta p|$ is smaller than p_{CUT}, this value and, therefore, the value of $\dot{V}$ in Eq. (15) will likely contain noise which should be damped. F_{NOISE} is constructed to tend towards 1 when $|\Delta p|$ is large relative to Δp_{CUT} and tends towards 0 when $|\Delta p|$ is small relative to Δp_{CUT}.

4. Define and calculate $\dot{V}_{EX}$ as the volume rate of flow exchanged through the vent between the two spaces because of an unstable cross-vent density configuration, i.e., when $\Delta\rho > 0$:

$$\text{If } \Delta\rho \leq 0: \quad \dot{V}_{EX} = 0 \tag{18}$$

If $\Delta\rho > 0$:

Calculate Δp_{FLOOD}:

$$\Delta p_{FLOOD} = C^2_{SHAPE} g \Delta\rho D^5/(2A^2_V) \tag{19}$$

where

$$C_{SHAPE} = \begin{cases} 0.754 \text{ for circular vents} \\ 0.942 \text{ for square vents} \end{cases} \tag{20}$$

Calculate $\dot{V}_{EX,MAX}$, the maximum value of $\dot{V}_{EX}$:

$$V_{EX,MAX} = 0.10[2g\Delta\rho A_V{}^{5/2}/(\rho_1 + \rho_2)]^{1/2} \tag{21}$$

Calculate $\dot{V}_{EX}$:

$$\dot{V}_{EX} = \begin{cases} V_{EX,MAX}(1 - |\Delta p|/|\Delta p_{FLOOD}|) & \text{if } |\Delta p|/|\Delta p_{FLOOD}| < 1 \\ 0 \text{ otherwise} \end{cases} \tag{22}$$

5. Define and calculate $\dot{V}_{VENT,I}$, I = 1 and 2, as the volume rate of the vent flow component entering space I.

$$\dot{V}_{VENT,I} = \dot{V}_{ST,I} + \dot{V}_{EX} \tag{23}$$

6. Calculate the vent flow properties $\rho_{VENT,I}$, $T_{VENT,I}$, $c_{VENT,O2,I}$, $c_{VENT,K,I}$, K = 2 to N_{PROD}, I = 1 and 2:

$$\rho_{VENT,1} = \rho_2, \quad \rho_{VENT,2} = \rho_1 \tag{24}$$

$$T_{VENT,1} = T_2, \quad T_{VENT,2} = T_1 \tag{25}$$

$$c_{VENT,O2,1} = c_{O2,2}, \quad c_{VENT,O2,2} = c_{O2,1} \tag{26}$$

$$c_{VENT,K,1} = c_{K,2}, \quad c_{VENT,K,2} = c_{K,1}, \quad K = 2 \text{ to } N_{PROD} \tag{27}$$

7. Calculate the vent flow rates $\dot{M}_{VENT,I}$, I = 1 and 2:

$$\dot{M}_{VENT,I} = \rho_{VENT,I}\dot{V}_{VENT,I} \tag{28}$$

8. Calculate the vent flow rates $\dot{Q}_{VENT,I}$, $\dot{P}_{O2,VENT,I}$, $\dot{P}_{K,VENT,I}$, K = 2 to N_{PROD}, I = 1 and 2:

$$\dot{Q}_{VENT,I} = \dot{M}_{VENT,I}C_pT_{VENT,I} \tag{29}$$

$$\dot{P}_{O2,VENT,I} = \dot{M}_{VENT,I}c_{VENT,O2,I} \tag{30}$$

$$\dot{P}_{K,VENT,I} = \dot{M}_{VENT,I}c_{VENT,K,I}, \quad K = 2 \text{ to } N_{PROD} \tag{31}$$

9. Calculate rates at which flows are added to layers of each space as a result of the vent flow extracted from it. First consider space 1 (I = 1, J = 2) and then space 2 (I = 2, J = 1). For either case:

If $\{[(y_{VENT} = y_{REF,I})$ and $(y_{LAYER,I} = y_{REF,I})]$ or

$[(y_{VENT} = y_{CEIL,I})$ and $(y_{LAYER,I} < y_{CEIL,I})]\}$

(i.e., the vent flow to room J is extracted from the upper layer of room I and, if space I is an inside room, the lower layer of room I is unchanged) then:

$$\dot{M}_{U,I} = -\dot{M}_{VENT,J}, \quad \dot{M}_{L,I} = 0 \tag{32}$$

$$\dot{Q}_{U,I} = -\dot{Q}_{VENT,J}, \quad \dot{Q}_{L,I} = 0 \tag{33}$$

$$\dot{P}_{O2,U,I} = -\dot{P}_{O2,VENT,J}, \quad \dot{P}_{O2,L,I} = 0 \tag{34}$$

$$\dot{P}_{K,U,I} = -\dot{P}_{K,VENT,J}, \quad \dot{P}_{K,L,I} = 0 \tag{35}$$

If $y_{REF,I} = y_{CEIL,I}$ (i.e., space I is an outside space) modify the results of Eq. (32)-(35) as follows:

$$\dot{M}_{L,I} = \dot{M}_{U,I} \tag{36}$$

$$\dot{Q}_{L,I} = \dot{Q}_{U,I} \tag{37}$$

$$\dot{P}_{O2,L,I} = \dot{P}_{O2,U,I} \tag{38}$$

$$\dot{P}_{K,L,I} = \dot{P}_{K,U,I} \tag{39}$$

If the condition above Eq. (32) is not satisfied

(i.e., the vent flow to room J is extracted from the lower layer of room I and, if space I is an inside room, the upper layer of room I is unchanged) then:

$$\dot{M}_{L,I} = -\dot{M}_{VENT,J}, \quad \dot{M}_{U,I} = 0 \tag{40}$$

$$\dot{Q}_{L,I} = -\dot{Q}_{VENT,J}, \quad \dot{Q}_{U,I} = 0 \tag{41}$$

$$\dot{P}_{O2,L,I} = -\dot{P}_{O2,VENT,J}, \quad \dot{P}_{O2,U,I} = 0 \tag{42}$$

$$\dot{P}_{K,L,I} = -\dot{P}_{K,VENT,J}, \quad \dot{P}_{K,U,I} = 0 \tag{43}$$

If $y_{REF,I} = y_{CEIL,I}$ (i.e., space I is an outside space) modify the results of Eqs. (40)-(43) as follows:

$$\dot{M}_{U,I} = \dot{M}_{L,I} \tag{44}$$

$$\dot{Q}_{U,I} = \dot{Q}_{L,I} \tag{45}$$

$$\dot{P}_{O2,U,I} = \dot{P}_{O2,L,I} \tag{46}$$

$$\dot{P}_{K,U,I} = \dot{P}_{K,L,I} \tag{47}$$

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SUBROUTINE VARIABLES

All nomenclature in the subroutine is identical to the nomenclature used above except for:

A_V - AVENT [m^2]

C - COEF

C_p - CP [W·s/(kg·K)]

C_{SHAPE} - CSHAPE [dimensionless]

$c_{L,K,I}$, $c_{U,K,I}$ - CONL(K,I), CONU(K,I), I = 1 or 2 [(unit of product K)/(kg of layer)]

$c_{L,O2,I}$, $c_{U,O2,I}$ - CONL(1,I), CONU(1,I), I = 1 or 2 [(kg of oxygen)/(kg of layer)]

$c_{VENT,K,I}$ - CVENT(K,I), I= 1 or 2 [(unit of product)/(kg of vent flow)

$c_{VENT,O2,I}$ - CVENT(1,I), I = 1 or 2 [(kg of oxygen)/(kg of vent flow)]

$c_{K,I}$ - C(K,I), I= 1 or 2 [(unit of product)/(kg of vent flow)

$c_{O2,I}$ - C(1,I), I = 1 or 2 [(kg of oxygen)/(kg of vent flow)]

F_{NOISE} - FNOISE [dimensionless]

f - FF [dimensionless]

g - 9.8 m/s^2

$\dot{M}_{L,I}$, $\dot{M}_{U,I}$ - XML(I), XMU(I), I = 1 or 2 [kg/s]

$\dot{M}_{VENT,I}$ - XMVENT(I) [kg/s]

N_{PMAX} - NPMAX [dimensionless]

N_{PROD} - NPROD [dimensionless]

N_{SHAPE} - NSHAPE [dimensionless]

$\dot{P}_{K,L,I}$, $\dot{P}_{K,U,I}$ - PL(K,I), PU(K,I), I = 1 or 2 [(unit of product K)/s]

$\dot{P}_{K,VENT,I}$ - PVENT(K,I), I = 1 or 2 [(unit of product K)/s]

$\dot{P}_{O2,L,I}$, $\dot{P}_{O2,U,I}$ - PL(1,I), PU(1,I), I = 1 or 2 [(kg of oxygen)/s]

$\dot{P}_{O2,VENT,I}$ - PVENT(1,I), I = 1 or 2 [(kg of oxygen)/s]

p_{DATUM} - PDATUM [Pa = kg/(m·s^2)]

p_I - P(I), I = 1 or 2 [Pa = kg/(m·s^2)]

$\dot{Q}_{L,I}$, $\dot{Q}_{U,I}$ - QL(I), QU(I), I = 1 or 2 [W]

$\dot{Q}_{VENT,I}$ - QVENT(I), I = 1 or 2 [W]

T_I - T(I), I = 1 or 2 [K]

$T_{L,I}$, $T_{U,I}$ - TL(I), TU(I), I = 1 or 2 [K]

$T_{VENT,I}$ - TVENT(I), I = 1 or 2 [K]

$\dot{V}$ - V [m^3/s]

$\dot{V}_{EX}$ - VEX [m^3/s]

$\dot{V}_{EX,MAX}$ - VEXMAX [m^3/s]

$\dot{V}_{ST,I}$ - VST(I), I = 1 or 2 [m^3/s]

$\dot{V}_{VENT,I}$ - VVENT(I), I = 1 or 2 [m^3/s]

w - W [dimensionless]

x - X [dimensionless]

$y_{REF,I}$ - YREF(I), I = 1 or 2 [m]

$y_{LAYER,I}$ - YLAY(I), I = 1 or 2 [m]

y_{VENT} - YVENT [m]

$y_{CEIL,I}$ - YCEIL(I), I = 1 or 2 [m]dimensionless]

γ - 1.40

Δp - DELP [Pa = kg/(m·s^2)]

$\Delta p_{CUT}^{1/2}$ - DPC1D2 [Pa = kg/(m·s^2)]

Δp_{FLOOD} - DELPFD [Pa = kg/(m·s^2)]

$\Delta\rho$ - DELDEN [kg/m^3]

δp_I - DP(I), I = 1 or 2 [Pa = kg/(m·s^2)]

$\delta p_{REF,I}$ - DPREF(I), I = 1 or 2 [Pa = kg/(m·s^2)]

ϵ - EPS [dimensionless]

ϵ_p - EPSP [dimensionless]

ρ - RHO [kg/m^3]

ρ_I - DEN(I), I = 1 or 2 [kg/m^3]

$\rho_{L,I}$, $\rho_{U,I}$ - DENL(I), DENU(I), I = 1 or 2 [kg/m^3]

$\rho_{VENT,I}$ - DENVNT(I), I = 1 or 2 [kg/m^3]

PREPARED BY

Leonard Y. Cooper
October 1990

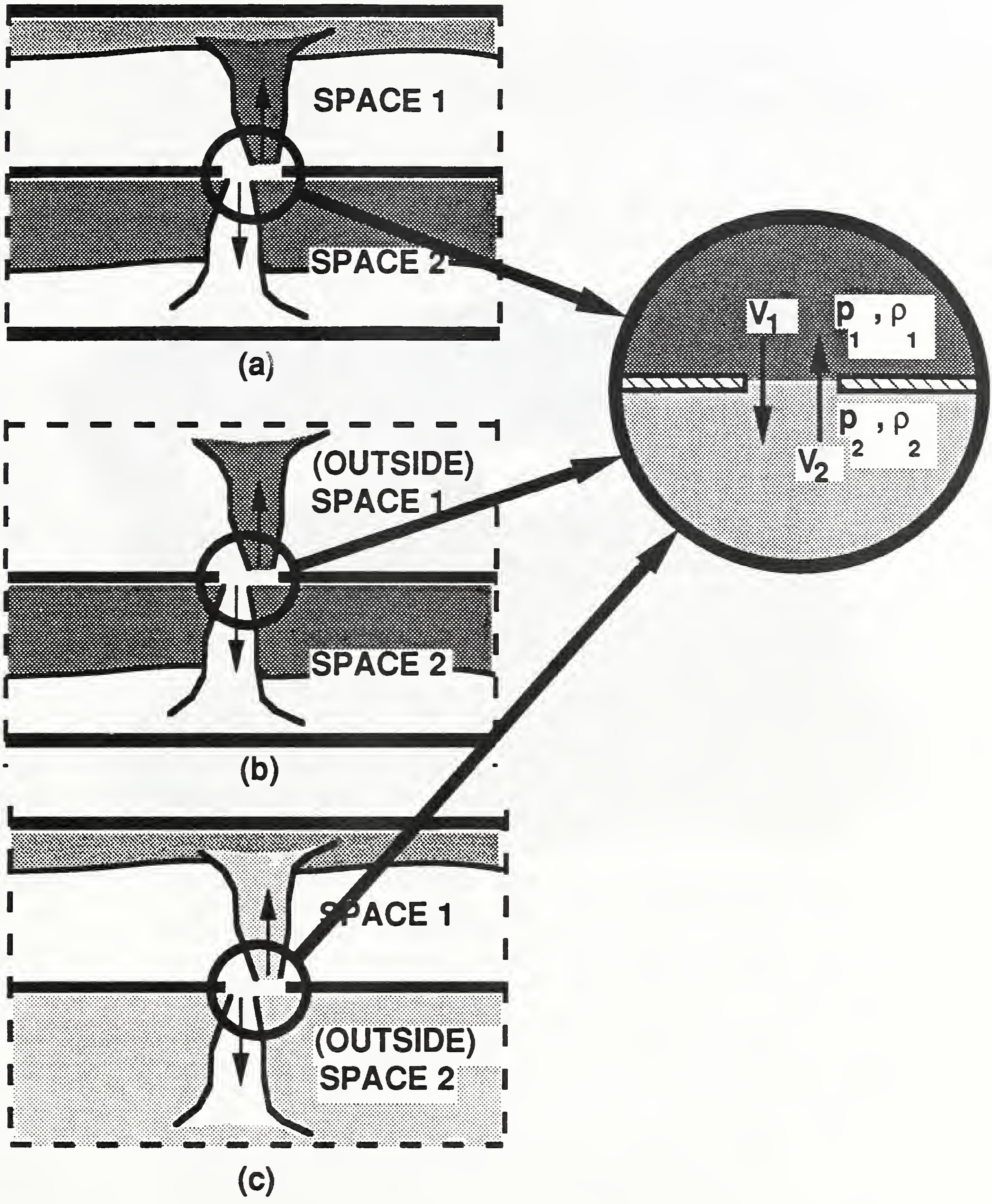

Figure 1. The possible configurations of the two spaces joined by a horizontal ceiling/floor vent with space 1 above space 2: a) two inside rooms; b) an outside space above an inside room; c) an inside room over an outside space.

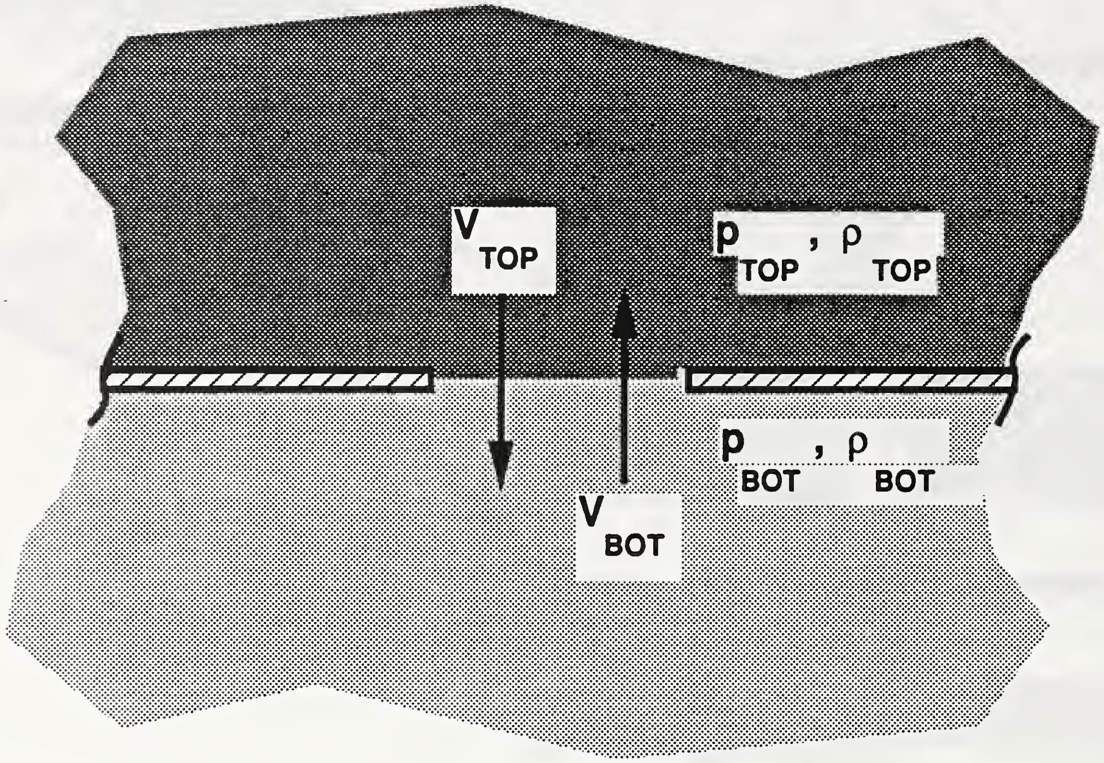

Figure 2. The geometry and conditions local to a horizontal ceiling/floor vent which determine the characteristics of the vent flow.

SUBROUTINE VENTCF

```
      SUBROUTINE VENTCF(
     I          AVENT,CONL,CONU,CP,D,NPMAX,NPROD,NSHAPE,PDATUM,TL,TU,
     I          YCEIL,YREF,YLAY,YVENT,DPREF,EPSP,DENL,DENU,
     O          C,CVENT,XML,XMU,XMVENT,PL,PU,PVENT,P,QL,QU,QVENT,T,TVENT,
     O          DELP,DEN,DENVNT)
       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*BEG
C***  VENTCF -     CALCULATION OF THE FLOW OF MASS, ENTHALPY, OXYGEN AND
C                  OTHER PRODUCTS OF COMBUSTION THROUGH A HORIZONTAL
C                  VENT JOINING AN UPPER SPACE 1 TO A LOWER SPACE 2. THE
C                  SUBROUTINE USES INPUT DATA DESCRIBING THE TWO-LAYER
C                  ENVIRONMENT OF INSIDE ROOMS AND THE UNIFORM
C                  ENVIRONMENT IN OUTSIDE SPACES.
C
C*** SUBROUTINE ARGUMENTS
C
C   INPUT
C   -----
C   AVENT        - AREA OF THE VENT [M**2]
C   CONL(K,I)    - CONCENTRATION OF PRODUCT K IN LOWER LAYER OF AN INSIDE
C                  ROOM I OR UNIFORM CONCENTRATION OF PRODUCT K IN AN
C                  OUTSIDE SPACE I [(UNIT OF PRODUCT)/(KG LAYER)]
C   CONL(K,I)    - CONCENTRATION OF PRODUCT K IN UPPER LAYER OF AN INSIDE
C                  ROOM I OR UNIFORM CONCENTRATION OF PRODUCT K IN AN
C                  OUTSIDE SPACE I [(UNIT OF PRODUCT)/(KG LAYER)]
C   CP           - SPECIFIC HEAT [W*S/(KG*K)]
C   D            - DIAMETER OF VENT FOR CIRCLE, LENGTH OF SIDE FOR SQUARE
C                  [M]
C   NPMAX        - MAXIMUM ALLOWED NUMBER OF PRODUCTS
C   NPROD        - NUMBER OF PRODUCTS IN CURRENT SCENARIO
C   NSHAPE       - NUMBER CHARACTERIZING VENT SHAPE: 1 = CIRCLE, 2 =
C                  SQUARE
C   PDATUM       - DATUM ABSOLUTE PRESSURE [PA = KG/(M*S**2)]
C   TL(I)        - TEMPERATURE OF LOWER LAYER OF AN INSIDE ROOM I OR
C                  TEMPERATURE OF AN OUTSIDE SPACE I [K]
C   TU(I)        - TEMPERATURE OF UPPER LAYER OF AN INSIDE ROOM I OR
C                  TEMPERATURE OF AN OUTSIDE SPACE I [K]
C   YCEIL(I)     - HEIGHT OF CEILING ABOVE DATUM ELEVATION FOR AN INSIDE
C                  ROOM I OR YREF(I) FOR AN OUTSIDE SPACE I [M]
C   YREF(I)      - HEIGHT OF REFERENCE ELEVATION FOR SPACE I ABOVE DATUM
C                  ELEVATION [M]
C   YLAY(I)      - HEIGHT OF LAYER ABOVE DATUM ELEVATION FOR AN INSIDE
C                  ROOM I OR YREF(I) FOR AN OUTSIDE SPACE I [M]
C   YVENT        - HEIGHT OF VENT ABOVE DATUM ELEVATION [M]
C   DPREF(I)     - PRESSURE IN SPACE I AT ITS REFERENCE ELEVATION ABOVE
C                  DATUM ABSOLUTE PRESSURE [PA = KG/(M*S**2)]
C   EPSP         - ERROR TOLERANCE FOR DPREF [DIMENSIONLESS]
C   DENL(I)      - DENSITY OF LOWER LAYER OF AN INSIDE ROOM I OR DENSITY
C                  OF AN OUTSIDE SPACE I [KG/M**3]
C   DENU(I)      - DENSITY OF UPPER LAYER OF AN INSIDE ROOM I OR DENSITY
```

```
C                  OF AN OUTSIDE SPACE I [KG/M**3]
C
C   OUTPUT
C   ------
C   C(K,I)       - CONCENTRATION OF EACH PRODUCT IMMEDIATELY ABOVE (IN
C                  SPACE I = 1) AND BELOW (IN SPACE I = 2) THE VENT
C                  [(UNIT OF PRODUCT)/(KG LAYER)]
C   CVENT(I)     - CONCENTRATION OF EACH PRODUCT IN THE VENT FLOW
C                  COMPONENT ENTERING SPACE I [(UNIT OF PRODUCT)/(KG OF
C                  VENT FLOW)]
C   XML(I)       - RATE AT WHICH MASS IS ADDED TO THE LOWER LAYER OF AN
C                  INSIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I =
C                  1 (I = 2) DUE TO THE VENT FLOW COMPONENT ENTERING
C                  SPACE = 2 (I = 1) [KG/S]
C   XMU(I)       - RATE AT WHICH MASS IS ADDED TO THE UPPER LAYER OF AN
C                  INSIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I = 1
C                  (I = 2) DUE TO THE VENT FLOW COMPONENT ENTERING SPACE
C                  I = 2 (I = 1) [KG/S]
C   XMVENT(I)    - MASS FLOW RATE IN THE VENT FLOW COMPONENT ENTERING
C                  SPACE I [KG/S]
C   PL(K,I)      - RATE AT WHICH PRODUCT K IS ADDED TO THE LOWER LAYER OF
C                  AN INSIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I
C                  = 1 (I = 2) DUE TO THE VENT FLOW CONPONENT ENTERING
C                  SPACE I = 2 (I = 1) [(UNIT OF PRODUCT)/S]
C   PU(K,I)      - RATE AT WHICH PRODUCT K IS ADDED TO THE UPPER LAYER OF
C                  AN INSIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I
C                  = 1 (I = 2) DUE TO THE VENT FLOW COMPONENT ENTERING
C                  SPACE I = 2 (I = 1) [(UNIT OF PRODUCT)/S]
C   PVENT(K,I)   - FLOW RATE OF PRODUCT K IN THE VENT FLOW COMPONENT
C                  ENTERING SPACE I [(UNIT OF PRODUCT)/S]
C   P(I)         - ABSOLUTE PRESSURE IMMEDIATELY ABOVE (IN SPACE I = 1)
C                  AND BELOW (IN SPACE I = 2) THE VENT [PA = KG/(M*S**2)]
C   QL(I)        - RATE AT WHICH ENTHALPY IS ADDED TO THE LOWER
C                  LAYER OF AN INSIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE
C                  SPACE I = 1 (I = 2) DUE TO THE VENT FLOW COMPONENT
C                  ENTERING SPACE I = 2 (I = 1) [W]
C   QU(I)        - RATE AT WHICH ENTHALPY IS ADDED TO THE UPPER LAYER OF
C                  AN INSIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I
C                  = 1 (I = 2) DUE TO THE VENT FLOW COMPONENT ENTERING
C                  SPACE I = 2 (I = 1) [W]
C   QVENT(I)     - FLOW RATE OF ENTHALPY IN THE VENT FLOW COMPONENT
C                  ENTERING SPACE I [W]
C   T(I)         - ABSOLUTE TEMPERATURE IMMEDIATELY ABOVE (IN SPACE I =
C                  1) AND BELOW (IN SPACE I = 2) THE VENT [K]
C   TVENT(I)     - ABSOLUTE TEMPERATURE OF THE VENT FLOW COMPONENT
C                  ENTERING SPACE I [K]
C   DELP         - CROSS-VENT PRESSURE DIFFERENCE, P(2) - P(1), [PA =
C                  KG/(M*S**2)]
C   DEN(I)       - DENSITY IMMEDIATELY ABOVE (IN SPACE I = 1) AND BELOW
C                  (IN SPACE I = 2) THE VENT [KG/M**3]
C   DENVNT(I)    - DENSITY OF THE VENT FLOW COMPONENT ENTERING SPACE I
C                  [KG/M**3]
```

```
C
C*END
      DIMENSION CONL(NPMAX,*), CONU(NPMAX,*), TL(*), TU(*)
      DIMENSION YCEIL(*), YREF(*), YLAY(*), DPREF(*)
      DIMENSION DENL(*), DENU(*)
      DIMENSION C(NPMAX,*), CVENT(NPMAX,*), XML(*), XMU(*)
      DIMENSION XMVENT(*)
      DIMENSION PL(NPMAX,*), PU(NPMAX,*), PVENT(NPMAX,*), P(*)
      DIMENSION QL(*),QU(*)
      DIMENSION QVENT(*), T(*), TVENT(*), DEN(*), DENVNT(*)
      DIMENSION DP(2), VST(2), VVENT(2)
      PARAMETER (GAM=1.40D0)
      DATA IFIRST/0/
      SAVE IFIRST,GAMCUT,GAMMAX
      PARAMETER (G=9.80D0)
C
C***  THE FOLLOWING CODE SEGMENT COMPUTES CONSTANTS REQUIRED BY VENTCF.
C***  IT IS EXECUTED THE FIRST TIME VENTCF IS CALLED.
C
      IF(IFIRST.EQ.0)THEN
            IFIRST = 1
            GAMCUT = (2.0D0/(GAM+1.0D0))**(GAM/(GAM-1.0D0))
            ZZZ=GAM*((2.0D0/(GAM+1.0D0))**((GAM+1.0D0)/(GAM-1.0D0)))
            GAMMAX = SQRT(ZZZ)
      ENDIF
C
C*** 1. AND 2.    CALCULATE THE P(I), DELP, THE OTHER PROPERTIES
C***              ADJACENT TO THE TWO SIDES OF THE VENT, AND DELDEN.
C
      DO 10 I = 1, 2
            IF(YREF(I).LE.YVENT.AND.YVENT.LE.YLAY(I))THEN
C
C***  THE VENT IS AT OR BELOW THE REFERENCE ELEVATION IN SPACE I.  IF
C***  SPACE I IS AN INSIDE ROOM THEN BOTH THE VENT AND THE LAYER
C***  INTERFACE ARE AT THE FLOOR ELEVATION.
C
                  DP(I) =  -  G*DENL(I)*(YVENT - YREF(I))
            ELSE
C
C***  THE VENT IS ABOVE THE REFERENCE ELEVATION IN SPACE
C***  IF SPACE I IS AN INSIDE ROOM THEN THE VENT IS AT THE
C***  CEILING.
C
                  DP(I) =  - G*DENL(I)*(YLAY(I)-YREF(I))
     $                                    - G*DENU(I)*(YVENT-YLAY(I))
            ENDIF
            P(I) = DPREF(I) + DP(I) + PDATUM
10    CONTINUE
C
C***  DELP IS PRESSURE IMMEDIATELY BELOW THE VENT LESS PRESSURE
C***  IMMEDIATELY ABOVE THE VENT.
C
```

```
      DELP = (DPREF(2)-DPREF(1))+(DP(2)-DP(1))
      DO 30 I = 1, 2
            DEN(I) = 0.0D0
            T(I) = 0.0D0
            DO 22 K = 1, NPROD
                  C(K,I) = 0.0D0
22          CONTINUE
            IF(((YVENT.EQ.YREF(I)).AND.(YLAY(I).EQ.YREF(I))).OR.
     $           ((YVENT.EQ.YCEIL(I)).AND.(YLAY(I).LT.YCEIL(I))))THEN
                  DEN(I) = DENU(I)
                  T(I) = TU(I)
                  DO 24 K = 1, NPROD
                        C(K,I) = CONU(K,I)
24                CONTINUE
            ELSE
                  DEN(I) = DENL(I)
                  T(I) = TL(I)
                  DO 26 K = 1, NPROD
                        C(K,I) = CONL(K,I)
26                CONTINUE
            ENDIF
30    CONTINUE
C
C***  DELDEN IS DENSITY IMMEDIATELY ABOVE THE VENT LESS DENSITY
C***  DENSITY IMMEDIATELY BELOW THE VENT
C
      DELDEN = DEN(1) - DEN(2)
C
C***  3. CALCULATE VST(I), THE "STANDARD" VOLUME RATE OF FLOW
C***     THROUGH THE VENT INTO SPACE I
C
C***  CALCULATE VST(I) IF DELP = 0
C
      IF(DELP.EQ.0.0D0)THEN
            VST(1) = 0.0D0
            VST(2) = 0.0D0
      ENDIF
C
C***  CALCULATE VST(I) FOR NONZERO DELP
C
      IF(DELP.GT.0.0D0)THEN
            VST(2) = 0.0D0
            RHO = DEN(2)
            EPS = DELP/P(2)
      ENDIF
      IF(DELP.LT.0.0D0)THEN
            VST(1) = 0.0D0
            RHO = DEN(1)
            EPS = -DELP/P(1)
      ENDIF
      X = 1.0D0 - EPS
      COEF = 0.68D0 + 0.17D0*EPS
```

```
      XO = 1.0D0
      EPSCUT = EPSP*MAX(XO,DPREF(1),DPREF(2))
      EPSCUT = SQRT(EPSCUT)
      SRDELP = SQRT(ABS(DELP))
      FNOISE = 1.0D0
      IF((SRDELP/EPSCUT).LE.130.D0)THEN
            FNOISE = 1.0D0 - EXP(-SRDELP/EPSCUT)
C
C***  NOTE: IF SINGLE PRECISION THEN USED 65. INSTEAD OF 130.
C
      ENDIF
      IF(EPS.LE.0.1D-5)THEN
            W = 1.0D0 - 0.75D0*EPS/GAM
      ELSE
            IF(EPS.LT.GAMCUT)THEN
                  GG = X**(1.0D0/GAM)
                  FF = SQRT((2.0D0*GAM/(GAM-1.0D0))*GG*GG*
     $                                             (1.0D0-X/GG))
            ELSE
                  FF = GAMMAX
            ENDIF
                  W = FF/SQRT(EPS+EPS)
      ENDIF
      V = FNOISE*COEF*W*SQRT(2.0D0/RHO)*AVENT*SRDELP
      IF(DELP.GT.0.0D0)VST(1) = V
      IF(DELP.LT.0.0D0)VST(2) = V
C
C***  4.  CALCULATE VEX, THE EXCHANGE VOLUME RATE OF FLOW
C***        THROUGH THE VENT
C
C***  STABLE CONFIGURATION, CALCULATE VEX = 0
C
      IF(DELDEN.LE.0.0D0)VEX = 0.0D0
C
C***  UNSTABLE CONFIGURATION, CALCULATE NONZERO VEX
C
      IF(DELDEN.GT.0.0D0.AND.AVENT.NE.0.0D0)THEN
            IF(NSHAPE.EQ.1)THEN
                  CSHAPE = 0.754D0
            ELSE
                        CSHAPE = 0.942D0
            ENDIF
            DELPFD = CSHAPE**2*G*DELDEN*D**5/(2.0D0*AVENT**2)
            DPDDPF = ABS(DELP/DELPFD)
            VEXMAX = 0.1D0*SQRT(2.0D0*G*DELDEN*SQRT(AVENT**5)
     $                                       /(DEN(1)+DEN(2)))
            VEX = MAX(VEXMAX*(1.0D0 - DPDDPF),0)
      ELSE
            VEX = 0.0D0
      ENDIF
C
C***  5.  CALCULATE VVENT(I), THE VOLUME RATE OF FLOW THROUGH
```

```
C***         THE VENT INTO SPACE I
C
      DO 40 I = 1,2
            VVENT(I) = VST(I) + VEX
40    CONTINUE
C
C***  6.  CALCULATE THE VENT FLOW PROPERTIES
C
      DENVNT(1) = DEN(2)
      DENVNT(2) = DEN(1)
      TVENT(1) = T(2)
      TVENT(2) = T(1)
      DO 50 K = 1, NPROD
            CVENT(K,1) = C(K,2)
            CVENT(K,2) = C(K,1)
50    CONTINUE
C
C***  7.  CALCULATE THE VENT MASS FLOW RATES
C
      DO 60 I = 1,2
            XMVENT(I) = DENVNT(I)*VVENT(I)
60    CONTINUE
C
C***  8.  CALCULATE THE REST OF THE VENT FLOW RATES
C
      DO 70 I=1,2
            QVENT(I) = XMVENT(I)*CP*TVENT(I)
            DO 65 K = 1, NPROD
                  PVENT(K,I) = XMVENT(I)*CVENT(K,I)
65          CONTINUE
70    CONTINUE
C
C***  9.  CALCULATE THE RATE AT WHICH THE VENT FLOWS ADD MASS,
C***         ENTHALPY, AND PRODUCTS TO THE LAYERS OF THE SPACES FROM
C***         WHICH THEY ARE EXTRACTED. FIRST TREAT LAYERS OF SPACE 1
C***         (I=1, J=2) AND THEN SPACE 2 (I=2, J=1).
C
      DO 95 I = 1, 2
            IF (I.EQ.1)THEN
                  J = 2
            ELSE
                  J = 1
            ENDIF
            IF(((ABS(YVENT-YREF(I)).LT.0.0001D0)
     $              .AND.(ABS(YLAY(I)-YREF(I)).LT.0.0001D0)).OR.
     $          ((ABS(YVENT-YCEIL(I)).LT.0.0001D0).AND.(YLAY(I)
     $            .LT.YCEIL(I))))THEN
                  XMU(I) = -XMVENT(J)
                  XML(I) = 0.0D0
                  QU(I) = -QVENT(J)
                  QL(I) = 0.0D0
                  DO 75 K = 1, NPROD
```

```
                     PU(K,I) = -PVENT(K,J)
                     PL(K,I) = 0.0D0
75             CONTINUE
               IF(ABS(YREF(I)-YCEIL(I)).LT.0.0001D0)THEN
                     XML(I) = XMU(I)
                     QL(I) = QU(I)
                     DO 80 K = 1, NPROD
                           PL(K,I) = PU(K,I)
80                   CONTINUE
               ENDIF
               ELSE
               XML(I) = -XMVENT(J)
               XMU(I) = 0.0D0
               QL(I) = -QVENT(J)
               QU(I) = 0.0D0
               DO 85 K = 1, NPROD
                     PL(K,I) = -PVENT(K,J)
                     PU(K,I) = 0.0D0
85             CONTINUE
               IF(ABS(YREF(I)-YCEIL(I)).LT.0.0001D0)THEN
                     XMU(I) = XML(I)
                     QU(I) = QL(I)
                     DO 90 K = 1, NPROD
                           PU(K,I) = PL(K,I)
90                   CONTINUE
               ENDIF
         ENDIF
95   CONTINUE
     RETURN
     END
```

NIST-114A
(REV. 3-90)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NISTIR 4402

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
October 1990

4. TITLE AND SUBTITLE
An Algorithm and Associated Computer Subroutine for Calculating Flow Through a Horizontal Ceiling/Floor Vent in a Zone-Type Compartment Fire Model

5. AUTHOR(S)
Leonard Y. Cooper

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)
U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)
Naval Research Laboratory
Washington, DC 20375

10. SUPPLEMENTARY NOTES

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

An algorithm and associated computer subroutine is presented for calculating the effects on two-layer compartment fire environments of the quasi-steady flow through a horizontal vent connecting two spaces. The two spaces can be either two inside rooms of a multi-room facility or one inside room and the outside ambient environment local to the vent. The description of the flow through the vent is determined by combining considerations of 1) the unidirectional-type of flow driven by a cross-vent pressure difference and, when appropriate, 2) the exchange-type of flow induced when the fluid configuration across the vent is unstable, i.e., when a relatively cool, dense gas in the upper space overlays a less dense gas in the lower space. In the algorithm, calculation of the rates of flow exchange between the two spaces is based on the previously developed theory presented in reference [1]. Characteristics of the geometry and the instantaneous environments of the two spaces are assumed to be known and specified as inputs. The outputs calculated by the algorithm/subroutine are the rates and the properties of the vent flow at the elevation of the vent as it enters the top space from the bottom space and/or as it enters the bottom space from the top space. Rates of mass, enthalpy, and products of combustion extracted by the vent flows from upper and lower layers of inside room environments and from outside ambient spaces are determined explicitly. The algorithm/subroutine is called VENTCF. The computer subroutine is written in FORTRAN 77. The subroutine is completely modular, and it is suitable for general use in two-layer, multi-room, zone-type fire model computer codes. It has been tested over a wide range of input variables and these tests are described.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

building fires; compartment fires; computer models; fire models; mathematical models; vents; zone models

13. AVAILABILITY
☒ UNLIMITED
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☐ ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
☒ ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES
53

15. PRICE
A04

ELECTRONIC FORM