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Ceiling Jet-Driven Wall Flows in Compartment Fires

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ABSTRACT

Analytic estimates are developed for depth of penetration and lateral entrainment of negatively buoyant, ceiling jet-driven wall flows during early times of compartment fire scenarios. When walls are not too far from the fire source, of the order of the fire-to-ceiling distance, it is found that the penetration of these downward wall flows is a large fraction of the fire-to-ceiling distance, and that this fraction is relatively independent of the details of fire size and fire-to-wall spacing. Also, net rate of entrainment into the wall flow as it is buoyed back upward to the ceiling elevation is found to be several times larger than the flow rate of the driving ceiling jet flow immediately upstream of wall impingement. Data from five studies reported in the literature are reviewed relative to the analytic results obtained. One of these involved a field model simulation of the flow generated by a buoyant source in an enclosure. Two experimental laboratory studies involved fires in enclosures with characteristic dimension of the order of several meters. Two others involved saltwater plumes in freshwater tanks with characteristic dimension of the order of several tenths of a meter. These data are found to be consistent generally with the analytic results, and, in particular, with the notion that the wall flows in question provide the mechanism for mixing which leads to the deep and rapid stratification typically observed in enclosed compartment fire environments.

Introduction

A major source of wall flows in compartment fires is the fire plume-driven ceiling jet which impinges on compartment walls at ceiling-wall junctures. Figure 1 depicts the wall flow phenomenon at the early stage of such a fire of total energy release rate, Q, before a significant upper smoke layer has formed. Figures and text in [1] depict and discuss later generic stages; first, when the wall flow of the type shown in Figure 1 penetrates an established, growing upper layer, and second, when an upper smoke layer completely submerges the ceiling jet and wall flow. As discussed in [1], at least the latter of these two stages can be analyzed once a predictive capability of the Figure 1 scenario is available. This paper will focus attention on the Figure 1 phenomena.

As depicted in Figure 2, the problem of obtaining a description of the characteristics of the wall flow can be broken into two isolated components. One of these is the problem of estimating characteristics of the ceiling jet immediately upstream of wall impingement. These characteristics must be obtained as a function of fire and compartment parameters. The second component is the problem of estimating the characteristics of a negatively buoyant wall flow as a function of a specified, downward-directed, negatively buoyant equivalent line-jet source positioned at the ceiling-wall juncture. The wall flow characteristics of interest here are δ_p, the extent of downward penetration of the negatively buoyant wall jet, and $(m'_{out} - m'_o)r_j$, the total rate per unit radian (of a circle centered at the plume-ceiling impingement point) at which far field ambient air is entrained laterally into the wall flow as it is buoyed back upward to the original ceiling elevation. With the solution to the two component problems in hand, a closure to the overall problem is achieved once conditions of ceiling jet turning at the ceiling-wall juncture are established and ceiling jet characteristics upstream of the juncture are thereby related to the properties of the equivalent line-jet source immediately downstream of the juncture.

Characteristics of the Ceiling Jet

It is known that for small to moderate values of r/H, inertial forces are generally large compared to buoyancy forces in buoyant plume-driven ceiling jets [2]. This fact was used in [3] to argue that the flow and heat transfer characteristics of buoyant plume-driven ceiling jets, like the one depicted in Figure 1, could be related directly to the analogous characteristics of wall or ceiling jets driven by unheated or weakly heated free turbulent jets (i.e., flows with the same configuration as Figure 1, but with a turbulent free jet replacing the fire and its buoyant plume). Thus, for the limited but important range of r/H up to the order of one, a ceiling jet driven by a plume would presumedly have approximately identical flow properties as that driven by an equivalent free jet. (This limitation on the r/H range is assumed throughout this work.) The criteria of equivalence proposed in [3] was that the mass and momentum of the plume and of the free jet be identical at their respective points of impingement. Applying these criteria, it has been possible to recorrelate results from the literature on free jet-driven wall flows and to apply the new correlations to data from buoyant plume-driven ceiling jet experiments, thereby obtaining estimates for the ceiling jet flow and heat transfer characteristics of interest in compartment fires [3-6]. Thus, results of [7-9] indicate that outside of the plume/ceiling impingement stagnation zone, defined approximately by $r/H > 0.2$, the radial velocity distribution, $V(Z)$, is essentially self-similar, and rises very rapidly from zero at the ceiling to a maximum, V_{max}, at a distance $Z = 0.23\delta$, δ being the distance below the ceiling where $V/V_{max} = 1/2$.

Applying further the above ideas, the following estimate for the velocity distribution of free jet-driven wall jets can be used directly for the analogous velocity distribution of the ceiling jet

$$V/V_{max} = \begin{cases} (8/7)[Z/(0.23\delta)]^{1/7}\{1-[Z/(0.23\delta)]/8\}, & 0 \le Z/(0.23\delta) \le 1 \\ \cosh^{-2}\{(0.23/0.77)\operatorname{arccosh}(2^{1/2})[Z/(0.23\delta)-1]\}, & 1 \le Z/(0.23\delta) \end{cases} \qquad (1)$$

The above result for the outer portion of the jet, $1 \le Z/(0.23\delta)$, is obtained from [9], and the inner jet velocity distribution is simply chosen to satisfy $V \sim Z^{1/7}$ at $Z = 0$ and $dV/dZ = 0$ at $V = V_{max}$. Finally [1],

$$V_{max}/\mathbf{V} = 0.85(r/H)^{-1.1} \;;\; \delta/H = 0.10(r/H)^{0.9} \qquad (2)$$

$$\mathbf{V} = g^{1/2}H^{1/2}Q^{*1/3} \;;\; Q^* = (1-\lambda_r)Q/(\rho_{amb}C_pT_{amb}g^{1/2}H^{5/2}) \qquad (3)$$

where g is the acceleration of gravity, λ_r is the fraction of Q radiated from the fire's combustion zone, and C_p is the specific heat at constant pressure, assumed to be constant.

Reference [10] reports results of measured V/V_{max} distributions in the range $0.2 \le r/H < 1.5$ under steady state conditions in reduced-scale, unconfined ceiling, plume-driven ceiling jets. Experimental parameters were in the range $H = 0.28\text{-}0.91$ m, $Q = 0.1\text{-}0.6$ kW, $Q^* = 0.3(10^{-2})\text{-}0.6(10^{-3})$, and the heat sources used to drive the the plumes were an electric heater, an ethane pool fire or a methane - air burner. The plume flow immediately upstream of ceiling impingement was turbulent in all experiments. Data plotted in Figure 10 of [10] are reproduced here in Figure 3 along with a plot of the present result of Eq. (3). ℓ in Figure 3 is defined by

$$V/V_{max}(Z = \ell) = 1/e \qquad (4)$$

where use of Eqs. (1) and (4) leads to the result

$$\ell = 1.17793\delta \qquad (5)$$

The far field plume description of [11] was used in the derivation of Eqs. (2). This includes the following estimate, which will be used below, for the mass flow rate of the plume at the elevation of ceiling impingement

$$m_{plume} = 0.21\rho_{amb}H^2\mathbf{V} \qquad (6)$$

Equations (1)-(3) provide a detailed velocity distribution of the ceiling jet. Once verified experimentally, this should prove useful in a variety of applications, e.g., for predicting the response of near-ceiling sprinkler links deployed at small-to-moderate r/H, and for specifying initial conditions in integral analyses of ceiling jets for larger r/H where buoyancy forces become comparable to and ultimately dominate inertial forces.

Integrated, rather than detailed ceiling jet properties will be used to resolve the present ceiling jet turning problem. For this reason the mass and momentum flux per unit width of the ceiling jet, m' and M', respectively, are defined and computed from Eqs. (1)-(3) and (6) as

$$m' = \rho_{amb} V_{max} \delta \int_0^\infty (V/V_{max}) d(Z/\delta) = 0.093 \rho_{amb} H V (r/H)^{-0.2}$$
$$= 2.8 (r/H)^{-0.2} m_{plume}/(2\pi H) \qquad (7)$$

$$M' = \rho_{amb} V_{max}^2 \delta \int_0^\infty (V/V_{max})^2 d(Z/\delta) = 0.059 \rho_{amb} H V^2 (r/H)^{-1.3} \qquad (8)$$

where near-constant density, $\rho \approx \rho_{amb}$, in the sense of the Bousinesq approximation, is assumed here and throughout the rest of this paper. The enthalpy flux per unit width, H', is also of interest. Thus

$$H' = \rho_{amb} C_p T_{amb} V_{max} \delta \int_0^\infty (V/V_{max})(T/T_{max} - 1) d(Z/\delta) = H'_{max}(1 - \lambda_c) \qquad (9)$$

$$H'_{max} = (1-\lambda_r)Q/(2\pi r); \quad \lambda_c = Q_{loss}/[(1-\lambda_r)Q]; \quad Q_{loss} = 2\pi \int_0^r q''_{ceiling} r dr \qquad (10)$$

where H'_{max} is the maximum possible value of H'; λ_c is the fraction of the plume's rate of convected enthalpy which is transferred out of the ceiling jet within a radius, r, of interest; and $q''_{ceiling}$ is the local flux of heat transfer out of the ceiling jet. λ_c will typically be at its maximum (H' at its minimum) at early times in a fire when the ceiling is uniformly near its initial temperature, T_{amb}. At such times, an estimate for λ_c as a function of r/H has been obtained in [1]. For the moderate r/H range of applicability, it will not exceed 0.3 for "typical" full-scale compartment fires with $(1-\lambda_r)Q$ in the range 200-2000 kW and H in the range 2-3 m.

Using m', M' and H', it will be useful to define a characteristic thickness, L^*, temperature difference, ΔT^*, and velocity, V^*, of the ceiling jet

$$L^* = m'^2/(\rho_{amb}M') \; ; \; V^* = M'/m'; \; \Delta T^* = T^* - T_{amb} = H'/(C_p m') \tag{11}$$

Characteristics of the Wall Flow

References [12] and [13] report the following correlations of experimental results for turbulent wall flows driven by negatively buoyant jet sources configured as in Figure 2.

$$\delta_p/D = 4.424Ri^{-0.389} \tag{12}$$

$$m'_{out}/m'_o = f(Ri) = 0.037+60.968Ri-238.056Ri^2+485.018Ri^3-381.35Ri^4 \tag{13}$$

$$0.02 \le Ri \le 0.5$$

where m'_o is the mass flux per unit width of the jet source, Ri is the jet Richardson's number based on the jet width, D, uniform exit velocity, V_o, and temperature, T_o,

$$Ri = Gr/Re^2 = g\Delta T_o D/(V_o{}^2 T_o) \ ; \ Gr = g\Delta T_o D^3/(T_o \nu_o{}^2) \ ; \ Re = V_o D/\nu_o \qquad (14)$$

and where $\Delta T_o = T_o - T_{amb}$ and ν_o is the kinematic viscosity at the jet source. Re, the jet Reynold's number, and Ri of the referenced experiments were in the range $1400 \le Re \le 4700$ and $0.02 \le Ri \le 0.5$, respectively. Presumedly the limits on Re are significant in the sense that the results are restricted to conditions of turbulent flow at the jet source. Thus, within the above experimental Ri range it is expected that the results of Eqs. (12) and (13) can be extended to jet sources with arbitrary Re greater than some minimum value which would distinguish between a laminar and turbulent source. In this regard, it is reasonable to expect this transition at $Re \approx 1000$ [14].

For the purpose of studying the properties of the wall flow, Z in the integrals of Eqs. (7)-(9) is now interpreted as the distance from the wall. Then m', M' and H', now designated as m'_o, M'_o and H'_o, respectively, are computed for the wall jet at its source. The definitions of Eqs. (11) are then applied to these results to obtain the following corresponding characteristic width, velocity and temperature of the source

$$L^*_{source} = m'^2_o/(\rho_{amb}M'_o) = D \; ; \; V^*_{source} = M'_o/m'_o = V_o ;$$

$$\Delta T^*_{source} = T^*_{source} - T_{amb} = H'_o/(C_p m'_o) = \Delta T_o = T_o - T_{amb} \quad (15)$$

The global properties of the finite thickness, negatively buoyant experimental jet source, m'_o, M'_o and H'_o, can be thought of as defining the properties of an equivalent line source of mass, momentum and enthalpy flux.

Using the Eq. (15) results for D, V_o, ΔT_o and T_o in terms of m'_o, M'_o and H'_o, δ_p/D of Eq. (12) and Ri and Re of Eq. (14) can be rewritten as

$$\delta_p/D = \delta_p \rho_{amb} M'_o/m'^2_o \; ; \; Re = m'_o/(\rho_{amb}\nu_o) \; ;$$

$$Ri = gH'_o m'^3_o/(\rho_{amb} C_p T_{amb} M'^3_o) \quad (16)$$

Ceiling Jet Turning and the Solution for m'_{out} and δ_p

Attention is focused at the position along a ceiling/wall juncture which is normal to a ray and at a distance, r_J, from the plume/ceiling impingement point. There, the turning downward of the ceiling jet is assumed to occur in such a manner as to preserve the magnitude of its mass, momentum and enthalpy flux, and, as a result, its characteristic jet thickness, velocity and temperature difference. Thus

$$m'_o = m'; \quad M'_o = M'; \quad H'_o = H'$$

$$L^*_o = L^*; \quad V^*_o = V^*; \quad \Delta T^*_o = \Delta T^* \tag{17}$$

Based on Eqs. (17), m', M' and H' from Eqs. (6)-(9) are substituted for m'_o, M'_o and H'_o, respectively, in Eqs. (16) to yield

$$Ri = 0.62(r_j/H)^{2.3}(1 - \lambda_c) \tag{18}$$

$$Re \approx 0.093(r_j/H)^{-0.2}ReH \; ; \; Re_H = g^{1/2}H^{3/2}Q*^{1/3}/\nu_{amb} \tag{19}$$

$$\delta_p/H = 0.78(1 - \lambda_c)^{-0.39} \approx 0.8 \text{ for "typical" full-scale fires} \tag{20}$$

$$m'_{out}/m'_o = \{m'_{out}/[m_{plume}/(2\pi r_j)]\}/[2.8(r_j/H)^{0.8}] = f(Ri) \tag{21}$$

where Re_H is a characteristic Reynold's number of the plume at its ceiling impingement point [3], and where the ≈ replaces the = in the first of Eq. (19) on account of the replacement of ν_o with ν_{amb} in the definition of Re. As a point of reference, the "typical" full-scale compartment fires mentioned earlier are in the Re_H range $2(10^5)$-$5(10^5)$. It is evident from the first of Eq. (19) that for these, and even for significantly smaller-scale fires, Re will exceed the $1000 < Re$ constraint mentioned below Eq. (14).

It is noteworthy that the results of Eqs. (17)-(21), including the $\delta_p/H \approx 0.8$ estimate of Eq. (20), would also hold in the small-Ri, large-Re range of buoyancy-conserving ceiling jets generated, for example, when salt water plumes are introduced into tanks of fresh water. For such situations, $\lambda_c = 0$ and $(1 - \lambda_r)Q/(C_p T_{amb})$ of Eq. (3) is replaced by $(\rho_{plume\ source} - \rho_{amb})$ X (volume flow rate of plume source).

Plots of Ri per Eq.(18) are presented in Figure 4 for the two extreme Re_H values 10^4 and 10^6, and for the two cases, $\lambda_c = 0$ and $\lambda_c(r_j/H) = \lambda_c^{(max)}$, its maximum possible value. In the latter case, $\lambda_c^{(max)}$ was calculated according to Eqs. (27) and (28) of [1] which are based on an estimate of heat transfer from the ceiling jet to an ambient temperature ceiling. The Figure 4 results were used to generate plots of m'_{out} per Eqs. (13), (18) and (21). These are presented in Figure 5.

Discussion of Results and Comparisons with Experiments

There are three surprising aspects to the results of Eq. (20) and Figure 5. These should be applicable for ceiling jet - wall impingement in the small-Ri range, which according to Eq. (18) and Figure 4 is to be expected in spaces with r_j/H up to 1 and possibly greater.

First, is the result of Figure 5. Compared to initial rates of smoke filling which would be estimated conventionally from m_{plume}, it is found that the smoke filling due to m'_{out} will be exceedingly large, approximately 5-20 times as great for a compartment with an effective r_j/H in the range 0.5-1.0. This result is always independent of source strength for buoyancy conserving flows and is relatively insensitive to source strength even when ceiling jet buoyancy losses due to ceiling heat transfer are at their highest levels.

Second is the result of Eq. (20) that δ_p/H is approximately independent of all fire and compartment parameters.

The final surprise is again found in the result of Eq. (20) which indicates that δ_p is almost as large as H itself. This suggests that the wall flow can be a significant mechanism for mixing throughout most of the horizontal slab of the compartment bounded by the elevation of the fire, i.e., the source of buoyancy, and the ceiling.

Indirect theoretical and laboratory experiment results having relevance to the current phenomenon are available in reports of studies involving a buoyant source in initially uniform ambient, enclosed compartments. The one theoretical work involved numerical experiments with a compartment fire field model. In two of the laboratory experiment studies, the buoyant source was a fire in an enclosure, while two others involved salt water - fresh water flows.

Of the two laboratory experiment fire studies, one [15] involved tests with H = 2.1m and Q^* between $1.(10^{-3})$ and $3.(10^{-3})$. The other [16] included a series of tests with H = 6.0m and Q^* between $0.2(10^{-3})$ and $1.(10^{-3})$. For all of these experiments $Re_H \geq 6.(10^4)$ and predicted conditions of the ceiling jet at r_J were such that all results of the previous sections should be applicable. Typical test results from thermocouple trees in each of these studies indicate that from an elevation outside of the ceiling jet region down to near the floor, and away from walls and the fire plume, the temperature distribution in the compartments could be reasonably described by a linear function of elevation. In general, low elevation thermocouples responded far more rapidly than would be predicted by a conventional, two-layer smoke-filling theory which didn't include a mechanism for upper layer - lower layer mixing. Also, it was reported in [15] that in some experiments, smoke movement down the walls was indicated by way of early increases in smoke concentration measured at the lowest smoke meter position located near the elevation of, but away from the burner source. All of these effects are consistent with the present results which predict an initial, deep, ceiling jet-driven wall flow which would likely lead to an early and continuing stratified distribution of the fire's products of combustion throughout most of the compartment height.

One of the two salt water studies [17] involved a buoyant source with Q^* between $0.9(10^{-5})$ and $5.(10^{-5})$, and with $Re > 1100$ in all experiments. In all test runs reported in Table IV of [17], flow visualization indicated that throughout the compartment, a turbulent region driven by the ceiling jet-driven wall flow grew quickly from the ceiling down to a thickness of about 0.55H. Below this, further gradual filling continued, but with laminar layering of a type described at length in [17]. The 0.55H result was insensitive to changes in Q^*, or in r_j/H, the latter of which varied between 0.5-1.0. It is possible to see the turbulent and laminar regions in Figure 6, which is a photograph of one of the experiments of [17] at a relatively late stage of filling.

The second of the salt water studies [18] involved a source with Q^* between $2.6(10^{-7})$ and $24.(10^{-7})$ and with $0.5 < r_j/H < 1.1$. From the data presented, Re was computed to be between 260 and 610. As in the previous study, it appears that a well-mixed near-ceiling layer was also formed rapidly. However, in these experiments the layer thickness varied significantly from test to test. The depth of wall flow overturning, which in [18] manifested itself in a non-uniform ring vortex motion, ranged from being non-discernable in the largest r_j/H cases to 0.8H in the smallest r_j/H cases. The difference between these data and the result of the present work, which predicts the well-mixed ceiling layer thickness to be a constant fraction of H independent of r_j/H, can be explained by the low values of Re. For the r_j/H range of approximately 1 or less, these are estimated to be significantly lower than Re values to be expected in most fire conditions of real interest and for which the present analysis is applicable. As mentioned earlier, a Re of less than 1000 is not likely to lead to the initially turbulent downward wall flow for which the data of [12], used in this study, are relevant.

Consistent with all the above results, it is noteworthy that [18] includes an order-of-magnitude estimate which concludes that significant wall overturning of plume driven flows is to be expected in relatively small r_j/H source-enclosure configurations.

The one theoretical study presents results for the transient development of a plume from a distributed source [19]. Calculations are carried out for different compartment configurations. Figure 12 of [19] presents results for a cubical compartment with energy source distributed near the floor. Prior to its expected overshoot and eventual upturn, this figure indicates a deep initial drop of the negatively buoyant wall flow to an elevation consistent with results of Eq. (20).

Summary and Conclusions

The main results of this work are in Eqs. (20) and (21). These provide estimates for the early depth of penetration of and the lateral entrainment into negatively buoyant, ceiling jet-driven wall flows which are generic to compartment fire scenarios.

When walls are not too far from the fire, of the order of the fire-to-ceiling distance, it is found that the penetration of the downward flow near such walls can be approximated by 0.8 of the fire-to-ceiling distance itself, and that this result is relatively independent of the details of fire size, spacings, etc. Also, net rate of entrainment into the wall flow as it is buoyed back upward to the ceiling elevation is found to be several times larger than the flow rate of the driving ceiling jet flow immediately upstream of ceiling jet - wall impingement.

Data from one theoretical and four experimental studies reported in the literature were reviewed relative to the analytic results obtained here. The theoretical study involved a field model simulation of conditions in a fully enclosed space with a distributed volumetric heat source near the center of the floor surface. Two of these studies involved fires in enclosures with characteristic dimension of the order of several meters. The other two involved saltwater plumes in freshwater tanks with characteristic dimension of the order of several tenths of a meter.

None of the above experimental studies were designed specifically to investigate the ceiling jet-driven wall flow phenomenon studied here. Also the analytic results were strictly valid only very early in a fire scenario, prior to any significant upper layer development, additional analysis being required to place quantitatively the ideas introduced here into the developing fire scenario. Yet, consistent with the results of this work and with the limited and indirect available data discussed above, it is reasonable to attribute to these wall flows the mechanism for mixing which leads to the deep and rapid stratification typically observed in enclosed compartment fire scenarios. Such rapid filling, heretofore unexplained by existing zone-type compartment fire models, can have a significant impact on parameters which characterize the dynamic compartment fire environment. Reasonably accurate estimates for such parameters are necessary if one is to predict, for example, the interactions between fire growth and the upper layer and the response of sprinkler links and smoke detectors. These are the predictions which must be used to resolve quantitatively issues of fire safety. In this regard, further analysis and more focused experimental study, e.g., using full- and reduced-scale enclosure fires and/or saltwater experiments, are required for confident application of ideas and results of this work to practical compartment fire modeling.

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Nomenclature

C_p	specific heat
D	thickness of wall flow source
Gr	Grashoff number of wall flow source, Eq. (12)
f	function of Ri, Eq. (10)
g	acceleration of gravity
H	distance from buoyant source to ceiling
H'	enthalpy flow per unit length of ceiling jet
H'_{max}	maximum possible H'
H_o'	enthalpy flow per unit length of wall flow source
L^*; L^*_{source}	characteristic thickness of ceiling jet; width of the wall flow source
ℓ	Z where V/V_{max} = 1/e, Eqs. (3) and (4)
M'; M'_o	momentum flow rate/unit lenght of ceiling jet; wall flow source
m_{plume}	mass flow rate of plume at ceiling
m'; m'_o; m'_{out}	mass flow rate/unit length of ceiling jet, Eq.(5); wall flow source; and wall flow, Fig. 2
Q	energy release rate of fire
Q_{loss}	rate of heat transfer from ceiling jet
Q^*	dimensionless Q, Eq.(3)
$q''_{ceiling}$	flux of heat transfer from ceiling jet
Re; Re_H	Reynold's number of wall flow source, Eq. (12); plume at impingement, Eq. (17)
Ri	Richardson's number of wall flow source, Eq.(12)

r	radial distance from plume impingement
r_j	r at ceiling-wall juncture
T_{amb}	ambient temperature
T_o	temperature of wall flow source
T^*; T^*_{source}	characteristic temperature of ceiling jet; wall flow source
V	velocity distribution of ceiling jet
V_{max}	maximum of V
$\mathbf{V}$; V^*; V^*_{source}	characteristic velocity of plume, Eq. (3); ceiling jet; wall flow source
V_o	velocity of wall flow source
Z	distance below ceiling
ΔT^*	$T^* - T_{amb}$
ΔT_o	$T_o - T_{amb}$
ΔT^*_{source}	$T^*_{source} - T_{amb}$
δ	Z where $V = V_{max}/2$
δ_p	penetration depth of wall flow
λ_c	fraction of $(1 - \lambda_r)Q$ transferred from ceiling jet
$\lambda_c^{(max)}$	maximum of λ_c
λ_r	fraction of Q radiated from fire
ν_{amb}; ν_o	dynamic viscosity of ambient; wall flow source
ρ_{amb}; $\rho_{plume\ source}$	density of ambient; plume source

List of Figures

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9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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)*

Analytic estimates are developed for the early depth of penetration of and the lateral entrainment into negatively buoyant, ceiling jet-driven wall flows which are generic to compartment fire scenarios. When walls are not too far from the fire source, of the order of the fire-to-ceiling distance, it is found that the penetration of the downward flow near such walls is a large fraction of the fire-to-ceiling distance itself, and that this fraction is relatively independent of the details of fire size, spacings, etc. Also, net rate of entrainment into the wall flow as it is buoyed back upward to the ceiling elevation is found to be several times larger than the flow rate of the driving ceiling jet flow immediately upstream of ceiling jet - wall impingement. Data from five studies reported in the literature are being reviewed relative to the analytic results obtained. One of these involves numerical experiments with a field model of the problem of a buoyant source in an enclosure. Two laboratory experimental studies involve fires in enclosures with characteristic dimensions of the order of several meters. Two others involve saltwater plumes in freshwater tanks with characteristic dimensions of the order of several tenths of a meter.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

ceilings; compartment fires; convective heat transfer; enclosure fires; fire plumes; fire modeling; heat transfer; room fires; walls

13. AVAILABILITY

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