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A Buoyant Source in the Lower of Two, Homogeneous, Stably Stratified Layers - A Problem of Fire in an Enclosure

U.S. DEPARTMENT OF COMMERCE
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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A BUOYANT SOURCE IN THE LOWER OF TWO, HOMOGENEOUS, STABLY STRATIFIED LAYERS - A PROBLEM OF FIRE IN AN ENCLOSURE

Leonard Y. Cooper

Abstract

A point source of buoyancy is located at a specified elevation within the lower of two, homogeneous, stably stratified layers. A turbulent buoyant plume is formed above the source, and it impinges on the layers' interface. Depending on the strength of the source, its position below the interface and on the density difference of the two layers, it is conjectured that either: (1) a central portion of the impinging plume flow will penetrate and continue upward into the far field of the upper layer as a buoyant plume, the outer portion of the flow penetrating but then dropping down toward the interface because of negative relative buoyancy; or (2) none of the impinging plume flow will penetrate the upper layer (indepth) because of its being uniformly of negative relative buoyancy. Associated with these possible conditions will be an effective horizontal outflow of fluid at the interface. The paper derives and solves a set of model equations for these plume-interface interactions, and the results are applied to a generic heat transfer problem related to fires in enclosures.

1. INTRODUCTION

The environment which develops within a fire-containing enclosure space is driven by the fire-generated buoyant plume. The fire products and the air entrained into the plume flow upward from the fire's combustion zone to the elevation of the initially ambient temperature ceiling surface. There, plume-ceiling impingement leads to an outwardly moving ceiling jet flow of the plume gases. These gases are eventually redistributed across the entire area of the enclosure ceiling, and an upper layer of elevated temperature, product-of-combustion-laden air (smoke) starts to fill the space from above. At some arbitrary time, t, into the fire, when the convected portion of the energy release rate is Q(t), the environment in the space of fire involvement and near the plume can be depicted as in Figure 1. The thickness of the upper smoke layer which submerges the continuing ceiling jet flow is $\Delta(t)$, and its lower interface is at an elevation, Z(t) above the fire. Data from many full scale fire experiments (e.g., references 1 and 2) indicate that it is reasonable to describe the bulk of the upper layer, outside the plume and boundary flows, as being of uniform composition, e.g., of uniform absolute temperature, $T_{up}(t)$. Indeed, this assumption is key to rendering tractable the problem of predicting the overall fire generated enclosure environment, and it has been used in almost every one of the several zone fire models which have been developed in recent years.

Mathematical modeling of the ceiling jet flow is very important in the development of rational design methods for fire safety. For example, it is the ceiling jet flow which would interact with properly deployed fire detectors, and with thermally actuated sprinklers, smoke vents and other fire intervention hardware. The rate of convective heat transfer from the ceiling jet to the ceiling surface material is also important, and it can be a significant fraction of Q(t) [2]. In designing for fire safety, reasonable quantitative estimates of this heat transfer are required for at least two reasons. First, the rate of heat transfer will determine the temperature and the eventual failure response of the ceiling structure. Second, the rate of heat transfer will determine the temperature and spread characteristics of the smoke layer. This is the smoke which eventually leads to an environment which is hazardous to life and/or property.

To describe the ceiling jet it is necessary to be able to estimate plume properties prior to ceiling impingement.

Prior to the time when the ceiling jet is submerged by the upper layer, or at times when ceiling jet temperatures are significantly larger than T_{up}, the Figure 1 scenario can be approximated by the unconfined ceiling problem depicted in Figure 2, i.e., the upper layer thickness and temperature rise above ambient do not greatly affect the ceiling jet properties, and the upper layer, whatever its thickness, can be assumed to have the properties of the ambient. Such situations would occur relatively early into the fire, later into the fire for very expansive ceilings, or when the fire strength is growing at a sufficiently rapid rate. Analytic descriptions of the ceiling jet for the unconfined ceiling problem have been presented in [3-5], where the fire in [3] and [5] was modeled as a point source of buoyancy.

A method for describing the ceiling jet for the more general Figure 1 scenario was presented in [6]. There, the concept of an "extended upper layer equivalent point source" is combined with the unconfined ceiling analysis of [5]. As depicted in Figure 3, the plume dynamics in the upper layer are described as being generated by a point source fire of strength Q', located a distance H' below the ceiling, and in an infinite "ambient" environment of temperature, T_{up}. The values Q' and H' are computed by invoking a principle of continuation which conserves plume mass and enthalpy flux across the upper layer interface. With Q' and H' in hand, the unconfined ceiling solution of [5] is used to predict heat transfer to the ceiling. This method gave analytic results which compared favorably to experimental data reported in [7].

Although it is reasonable to expect that the above method will provide excellent results when relatively strong plumes penetrate the layer interface, it will be inadequate when the plumes are relatively weak. Weak here refers to situations where the penetrating lower plume flow, having, say, a Gaussian distribution of temperature and velocity, is such that a significant outer portion, possibly the entire flow, is at a lower temperature than T_{up}. As such a plume enters the upper layer, this outer portion of the flow will be negatively buoyant relative to the "new" ambient, and it will tend to be separated off from the core flow, never to penetrate to the ceiling. The core flow will be positively buoyant relative to the upper layer, and it can be expected to continue its ascent to the ceiling as a buoyant plume. It is also possible that the negatively buoyant portion of the plume flow will shear off some of the core flow as it separates, or visa versa. If the excess enthalpy flux, $\bar{H}_R$, of the penetrating plume flow relative to the upper, T_{up} environment is negative, and if even its maximum temperature, $\bar{T}_{max}$, is less than or equal to T_{up} (as may be the case subsequent to decay phases of the fire), then it is reasonable to expect that all of this flow will be effectively redirected laterally near the interface. For large enough Δ, none of it will rise to the ceiling. The resulting flows in the upper layer near the interface would be similar to those studied in [8]. Here, H_R^- is defined as

$$H_R^- = 2\pi\, C_p \int_0^\infty \rho^- u^- \,(T^- - T_{up}) r dr \tag{1}$$

where u^-, ρ^-, and T^- are the flow velocity, density, and temperature, respectively, in the plume directly below the interface. Also, C_p is the specific heat which is assumed constant.

By adding and subtracting T_{amb} in the above parentheses and regrouping terms it is possible to rewrite eq. (1) as

$$H_R^- = Q - C_p\, T_{amb}\, (T_{up}/T_{amb} - 1)\, m^- \tag{2}$$

where m^- is defined as the mass flux in the plume immediately below the interface,

$$m^- = 2\pi \int_0^\infty \rho^- u^- r dr \tag{3}$$

and where, by conservation of energy, Q is the enthalpy flux of the plume below the interface,

$$Q = 2\pi\, C_p \int_0^\infty \rho^- u^- \,(T^- - T_{amb})\, r dr \tag{4}$$

By defining the following dimensionless variables

$$H_R^{*-} = H_R^-/Q; \quad m^{*-} = m^- C_p T_{amb}/Q; \quad \alpha = T_{up}/T_{amb} \tag{5}$$

Eq. (2) becomes

$$H_R^{*-} = 1 - (\alpha - 1)\, m^{*-} \tag{6}$$

It is the purpose of this paper to extend the method of [6] in such a way that the ceiling jet problems related to the scenario of Figure 1 can be described quantitatively for fires of arbitrary strength.

2. THE MODEL EQUATIONS

Consistent with the above discussion, sketches of the real and idealized flow are presented in Figure 4. The outflowing arrows in the idealized sketch represent two components of the outward-moving mass flow, I_m^+ and I_m^-, above and below the interface, respectively. These flows are taken to be at the respective ambient temperatures, T_{amb} and T_{up}, of the local environments into which they are flowing. Note that the two distinct outward flowing mass sources, I_m^+ and I_m^-, can be thought of as representing either a single idealized source, at some temperature between T_{up} and T_{amb}, or as an actual outward moving flow with some nonuniform temperature distribution. It is also noteworthy that the model being proposed does not distinguish possible flows involving portions of I_m^+ and/or I_m^- turning back, and being entrained into the plume either above (I_m^+) or below (I_m^-) the interface.

When $T_{max}^- \leq T_{up}$, all of the penetrating lower plume flow has negative buoyancy relative to the upper layer, and it will all eventually be turned downward, back toward the interface and away from the axis as in Figure 4a. For such completely turned flows, it is not useful to invoke conservation of vertical momentum in the present global model. To do so would lead to an equation which relates momentum flux of the plume at the interface to an integral of the pressure distribution along the upper boundary of some control volume, e.g., along the ceiling surface. Using the same reasoning when $T_{max}^- > T_{up}$ (and the incoming lower layer plume is partially overturned near the interface and partially continued as an upper layer buoyant plume), continuity of momentum will still not provide, here, useful additional information.

As in Figure 4b, when $T_{max}^- > T_{up}$ the portion of the penetrating plume flow which continues upward in the upper layer is designated by m^+, where

$$m^+ = m^+(z > Z) = 2\pi \int_0^\infty \rho^+ u^+ \, r dr \qquad (7)$$

and where ρ^+ and u^+ are the density and upward velocity, respectively above the interface. The ceiling is assumed to be far enough above the interface so that, at the elevation of ceiling impingement this upper layer buoyant plume can be adequately described as being equivalent to a flow driven by a point source of some unknown buoyant strength $Q' = H_R^+$ located a distance H' below the ceiling in an extended infinite environment of uniform temperature, T_{up}. Here, Q' is defined by

$$Q' = 2\pi C_p \int_o^\infty \rho^+ u^+ (T^+ - T_{up}) \, rdr \tag{8}$$

where T^+ is the temperature distribution above the interface. ρ^+, u^+ and T^+ are also the values of the variables that would occur at $z < Z$ as a result of the equivalent buoyant source being located in the extended upper layer, i.e., as in the scenario depicted in Figure 3.

Defining the dimensionless variables

$$\begin{aligned} I_m^{*+} &= I_m^+/m^- ; \quad I_m^{*-} = I_m^-/m^- ; \\ m^{*+} &= m^+/m^- ; \quad H_R^{*+} = Q'/Q \end{aligned} \tag{9}$$

continuity of mass and energy across the interface leads to

$$m^{*+}(z = Z) + I_m^{*+} + I_m^{*-} = 1 \tag{10}$$

$$H_R^{*+} + (\alpha - 1)(1 - I_m^{*-})m^{*-} = 1 \tag{11}$$

$$m^{*+} = H_R^{*+} = 0 \text{ if } T_{max}^- \leq T_{up} \tag{12}$$

Eqs. (10) and (11) are for the four variables I_m^{*+}, I_m^{*-}, $m^{*+}(Z)$, H_R^{*+}. For the case $T_{max}^- > T_{up}$, when the latter two of these are expected to be nonzero, two more equations are required. In this case it is assumed that the continuing flow, $m^+(Z)$, is all from a radial core region, $r \leq r_o$, of the plume mass flux, m^-. Then the first of the additional equations will reflect the assumption that the enthalpy flux between this core flow and $m^+(Z)$ is conserved across the interface. Thus, r_o is defined by

$$m^{+}(Z) = 2\pi \int_{o}^{r_o} \rho^{-} u^{-} r dr \tag{13}$$

and the conserved enthalpy flux assumption leads to

$$H_R^{*+} + (\alpha-1) m^{*-} m^{*+}(Z) = 2\pi (C_p/Q) \int_{o}^{r_o} \rho^{-} u^{-} (T^{-} - T_{amb}) r dr \tag{14}$$

The second equation will require that the peak temperature of the plume (i.e. at the axis) be continuous across the interface, viz,

$$T_{max}^{-} = T^{-}(r = 0) = T^{+}(Z,\ r = 0) > T_{up} \tag{15}$$

It is noteworthy that in the work of [9], which treats aspects of the upper layer plume dynamics in some detail, considerable importance is attached to this requirement which was ignored in [6].

2.1 The Point Source Plume and the Model Equations

The model equations (10)-(15) will now be developed further with the use of the point source buoyancy plume description of [10], viz,

$$(T - T_\infty)/(T_{max} - T_\infty) = \exp\,[-\beta r^2/(C_\ell^2 \zeta^2)] \tag{16}$$

$$u/u_{max} = \exp\,[-r^2/C_\ell^2 \zeta^2)] \tag{17}$$

where

$$T_{max} = (1 + C_T\, \Omega^{*2/3})\, T_\infty \tag{18}$$

$$u_{max} = C_v g^{1/2} \zeta^{1/2} \Omega^{*1/3} \tag{19}$$

$$\Omega^* = \Omega/(\rho_\infty C_p T_\infty \zeta^{5/2} g^{1/2}) \tag{20}$$

$$\begin{aligned} &\beta C_v^2 = 3C_T/2; \quad (1+\beta)/C_v = \pi C_T C_\ell^2; \\ &C_T = 9.115; \quad \beta = 0.913 \end{aligned} \tag{21}$$

In the above, T and u are the absolute temperature and vertical velocity in a plume at a distance ζ above a point source of convected enthalpy of strength Ω which is submerged in an ambient environment of uniform density, ρ_∞, and absolute temperature, T_∞. Also, g is the acceleration of gravity, and T_{max} and u_{max} are the maximum (centerline) values of T and u.

If m_{BP} is the mass flux in the buoyant plume, then the above description, together with the Boussinesq approximation in the form $\rho(Z,r) \approx \rho(Z,\infty)$ leads to

$$m_{BP} = [(1+\beta)/C_T]\ \rho_\infty g^{1/2} \zeta^{5/2} \Omega^{*1/3} \tag{22}$$

where, from eq. (21), $(1+\beta)/C_T = 0.210$

Define

$$\Gamma = \bar{T}_{max}/T_{up} - 1 > T_{amb}/T_{up} - 1 = -(\alpha-1)/\alpha \tag{23}$$

Then, from eq. (18)

$$\Gamma = (1 + C_T Q^{*2/3})/\alpha - 1 \tag{24}$$

where Q^* is defined by eq. (20) with Ω, ρ_∞, T_∞ and ζ replaced by Q, ρ_{amb}, T_{amb} and Z, respectively. Using the plume equations further, eqs. (10)-(15) lead to

$$\text{If } \Gamma \leq 0 : m^{*+}(Z) = 0 \tag{25}$$

If $\Gamma > 0$: $m^{*+}(Z)$ is the solution to

$$(\beta+1+\sigma)m^{*+}(Z)/(1+\sigma) = 1-[1-m^{*+}(Z)]^{1+\beta} \tag{26}$$

where

$$-1 < \sigma = \alpha\Gamma/(\alpha-1) \tag{27}$$

Also

$$I_m^{*-} = \{\beta - \sigma[1+m^{*+}(Z)]\}/(1+\beta) \tag{28}$$

$$I_m^{*+} = 1 - I_m^{*-} - m^{*+}(Z) \tag{29}$$

$$H_R^{*-} = (\sigma - \beta)/(1 + \sigma) \tag{30}$$

$$Q'/Q = \sigma m^{*+}(Z)/(1 + \sigma) \tag{31}$$

$$(H'-\Delta)/(H-\Delta) = \alpha^{3/5}[m^{*+}(Z)]^{2/5}[(1+\sigma)/\sigma]^{1/5} \tag{32}$$

2.2 Solution

A numerical solution to eq. (26) for $m^{*+}(Z)$, $\sigma > 0$ has been obtained and is plotted up to moderate values of σ in Figure 5. From the numerical results, the following analytic estimate for $m^{*+}(Z)$, accurate to within 0.05% in the entire range $\sigma > 0$, (well beyond any fire modeling requirements) has also been obtained

$$m^{*+}(Z) = \frac{1.04599\sigma + 0.360391\sigma^2}{1. + 1.37748\sigma + 0.360391\sigma^2} \tag{33}$$

The remaining variables in the model were found from eqs. (28)-(32), and are plotted in Figure 5.

3. COMPARISONS BETWEEN MODEL RESULTS AND EXPERIMENTAL DATA

3.1 Upper Layer Centerline Plume Temperatures

Reference [9] provides one set of experimental data for upper layer centerline plume temperatures in a Figure 1 scenario. In that experiment, the energy source was a 0.62 kW fire from a premixed (to minimize flame length) burner with 36.5 mm exit diameter. The experimental conditions along with the temperature data are presented in Figure 6. Consistent with these conditions

$$\alpha = 1.098; \ \Gamma = 0.286; \ \sigma = 3.20 \tag{34}$$

Using these in the results of the previous section leads to an analytic estimate for the plume centerline temperature distribution, which is also plotted in Figure 6. The agreement between measured and calculated results is such that $|(T_{meas}-T_{calc})/(T_{meas}-T_{amb})|$ never exceeds 0.14 in the upper layer.

3.2 Heat Transfer to the Ceiling

Reference [7] provides data for the radial and time-dependent convective heat transfer, $q_{measured}$, to an initially ambient temperature ceiling in a Figure 1 scenario. Measurements were taken at seven r/H values ranging from 0-0.72 and at 1, 2, 3 and 5 minutes into the test. The time-dependent values of the ceiling surface temperatures were also reported at these locations and times. The basic experimental conditions for the test were

$$H = 0.584 \text{ m}; \ \Delta = 0.31 \text{ m}; \qquad Q = 1.530 \text{ kW}; \ T_{amb} = 290^{\circ}K \tag{35}$$

Describing the upper layer environment according to the unconfined ceiling scenario of Figure 3, estimating Q'(t) and H'(t) with the use of the results of eqs. (31)-(33) and estimating the ceiling heat transfer according to the method developed in [5] leads to estimates of ceiling heat transfer rates, $q_{predicted}$.

The above procedure was followed, and the resulting values for $q_{predicted}/q_{measured}$ are plotted in Figure 7. The values of $q_{predicted}$ and $q_{measured}$ at the seven radial positions were used to estimate the instantaneous total rates of convective heat transfer, $2\pi\int q_{predicted} r dr$ and $2\pi\int q_{calculated} r dr$, to the experimental ceiling surface. For 1, 2, 3 and 5 minutes into the test the values of $\int q_{predicted} r dr / \int q_{measured} r dr$ were 0.82, 0.88, 0.93, and 0.92, respectively. Predicted values for m^{*+} were also obtained at these four times. These were found to be 0.89, 0.87, 0.85, and 0.83, respectively (σ = 7.56, 6.18, 5.43, and 4.64).

The present comparisons between predicted and measured heat transfer results are not significantly different from those obtained in [6]. In view of the above estimates of $m^{*+} \geq 0.83$ (i.e., m^{*+} close to 1), this comes as no particular surprise since the model of [6] includes the assumption that $m^{*+} \equiv 1$. However, in contrast to the present model, the reference (6) model must eventually fail for small m^{*+} (i.e., small σ) fire scenarios.

While it is reasonable to hope that the presently proposed calculation scheme will provide useful ceiling heat transfer results even for fire scenarios with moderate and small values of σ, further experimental verification of its utility is clearly required.

When $-1 < \sigma \leq 0$, the present model predicts a quiescent upper layer with no plume rising to the elevation of the ceiling. In such cases the convective/conductive heat transfer to the ceiling surface would be relatively small, the result, say, of a thick slab of quiescent, T_{up} gas which is cooled and/or heated from above by a relatively nonuniform ceiling surface.

4. SUMMARY AND CONCLUSIONS

Consistent with the sketches of Figure 4, a set of model equations to describe the plume dynamics in enclosure fire scenarios was derived. The solutions to the equation are plotted in Figure 5, and they are algebraically represented by eqs. (25)-(32), where eq. (26) is replaced by eq. (33).

Although the model equations and their solutions are remarkably simple, they were found to provide useful predictions to plume centerline temperatures, and to convective ceiling heat transfer in Figure 1 fire scenarios. In this regard, further experimental verification of the results over a broader range of model parameters is encouraged.

5. ACKNOWLEDGMENTS

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7. NOMENCLATURE

C_ℓ, C_v, C_T	constants, eq. (21)
C_p	specific heat
H	distance between ceiling and Q source
H'	distance between ceiling and Q' source
H_R	enthalpy flux of plume relative to T_{up}
H_R^*	H_R/Q, dimensionless
I_m	outward mass flux near interface
I_m^*	I_m/m^-, dimensionless
m	mass flux of plume
m^{*-}	dimensionless m^-, eq. (5)
m^{*+}	dimensionless m^+, eq. (9)
Q	convected portion of energy release rate
Q'	an upper layer equivalent source strength
Q^*	dimensionless Q, c.f. below eq. (24)
r	distance from plume axis
T	absolute temperature
T_{max}	maximum (axial) T of plume
t	time
u	upward velocity
u_{max}	maximum u of plume
Z	z of interface
z	elevation above buoyant source
α	T_{up}/T_{amb}
β	a constant, eq. (21)
Γ	a parameter, eqs. (23) and (24)
Δ	upper layer thickness
ζ	elevation above point source of buoyancy
ρ	density
σ	a parameter, eq. (27)
Ω	strength of a point source of buoyancy

Subscripts

amb, ∞	ambient
up	upper layer
BP	buoyant plume

Superscripts

$+$	above interface
$-$	immediately below interface

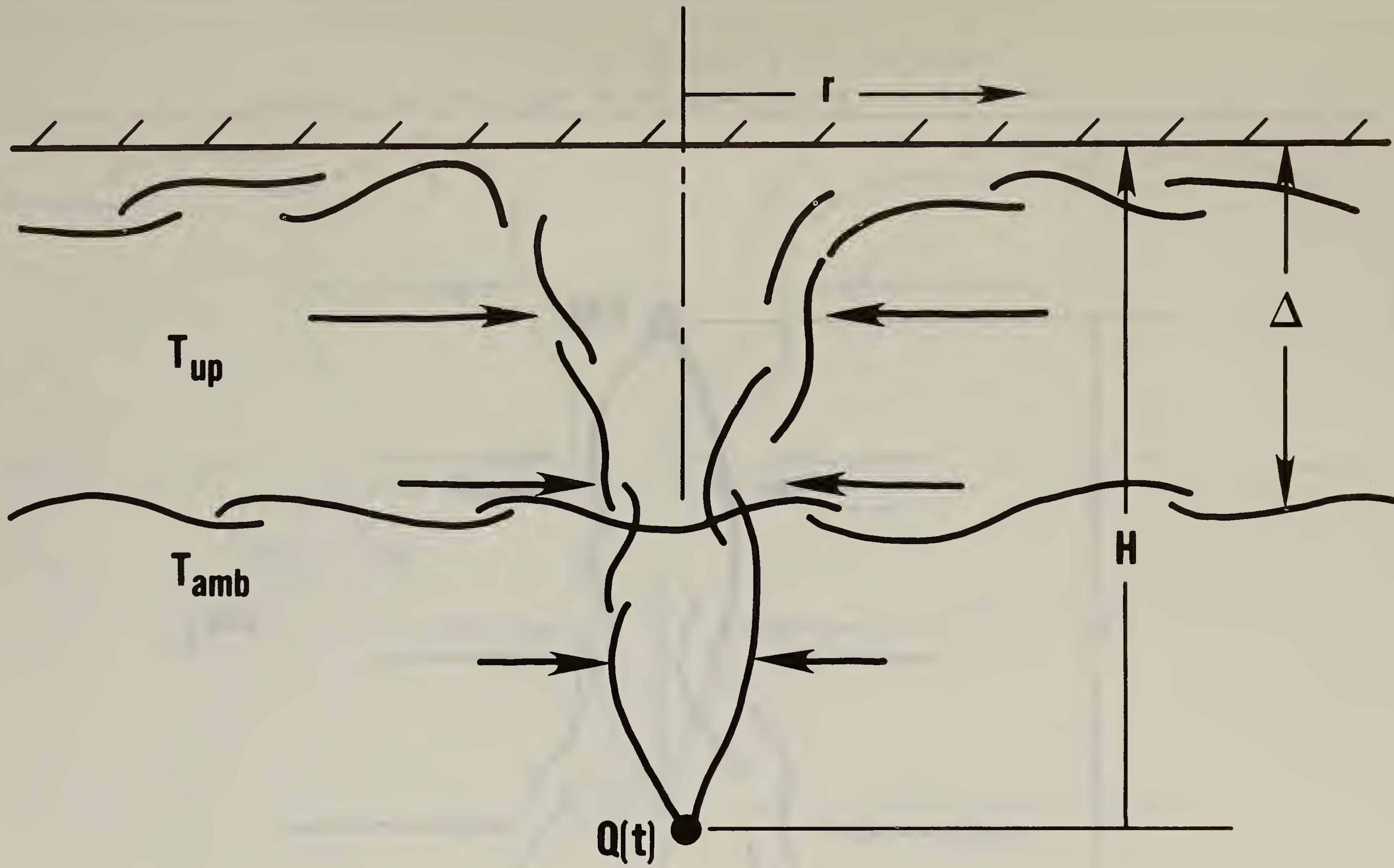

Figure 1. Environment near the plume in a room of fire involvement.

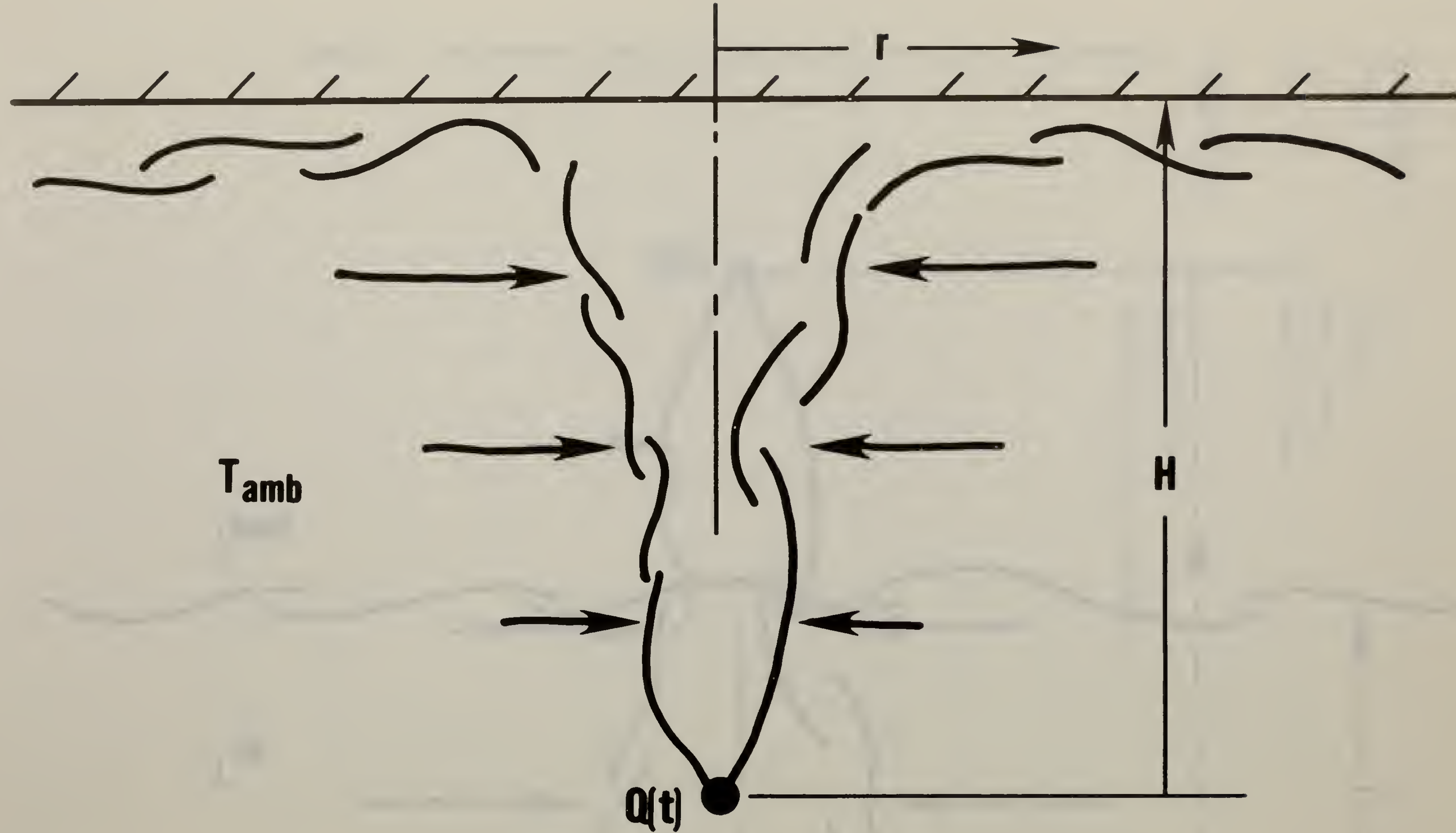

Figure 2. The early time, or unconfined ceiling fire environment.

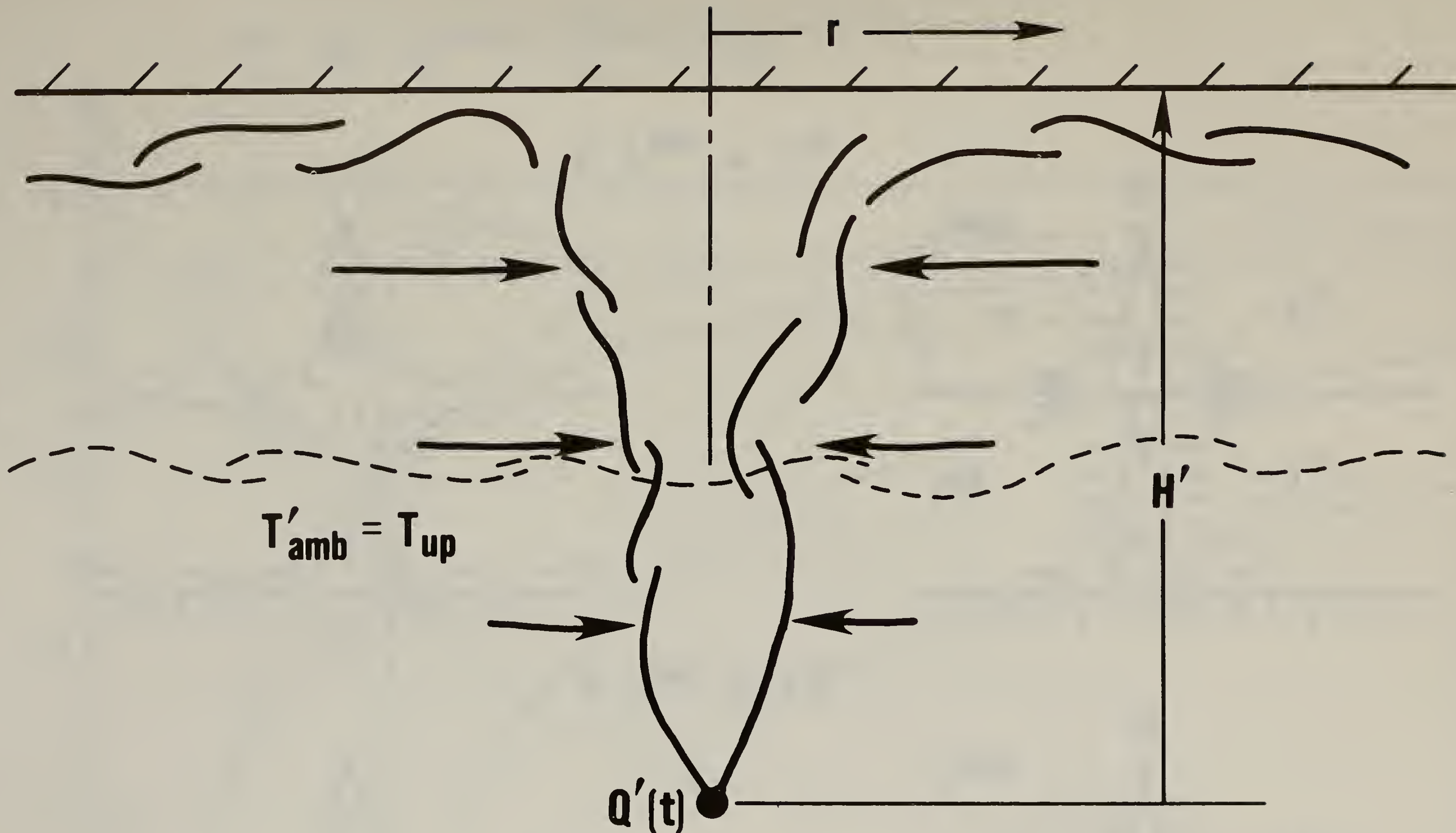

Figure 3. An equivalent unconfined ceiling fire environment for describing the upper layer plume and ceiling jet dynamics of Figure 1.

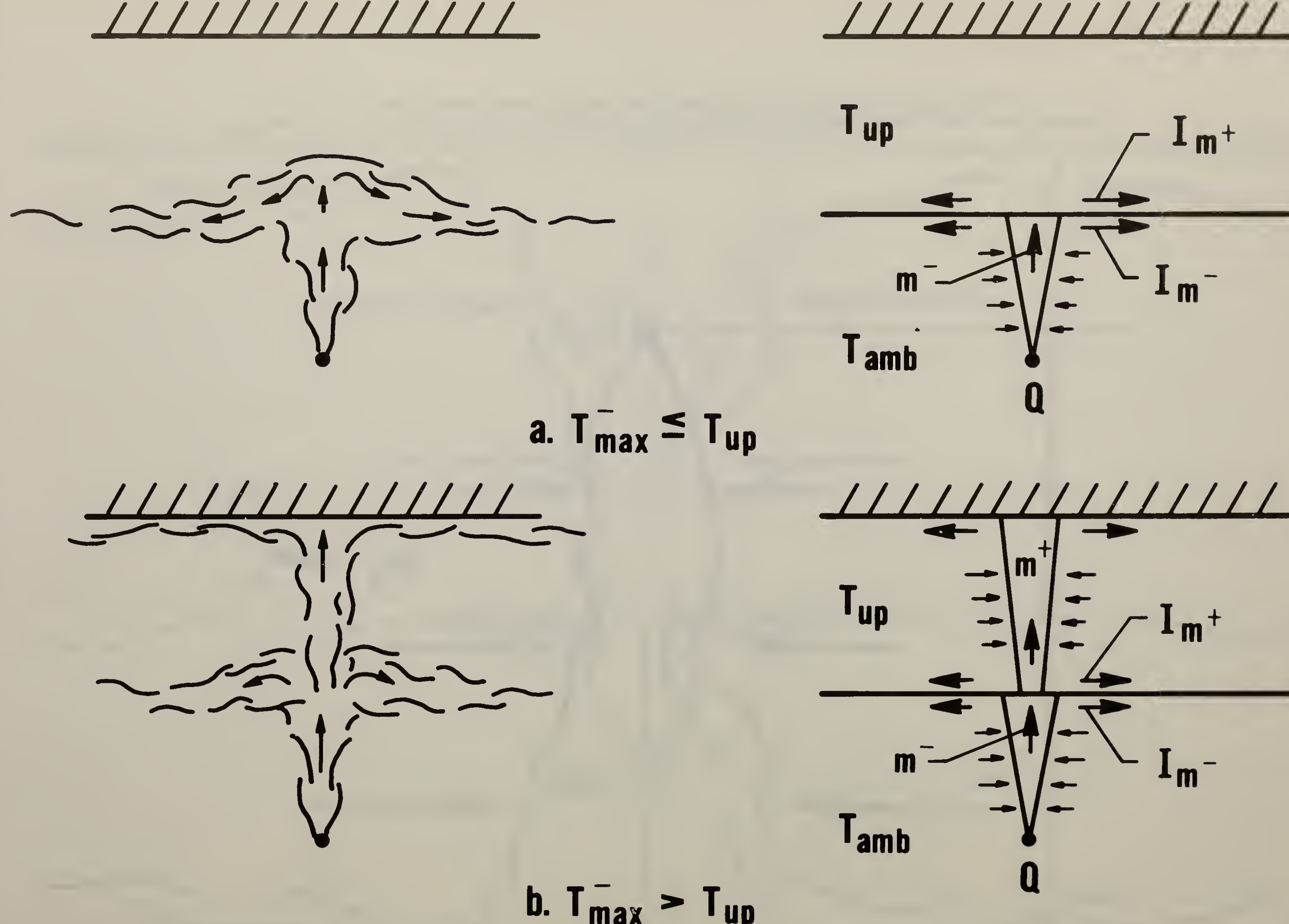

Figure 4. Sketches of real and idealized flows.

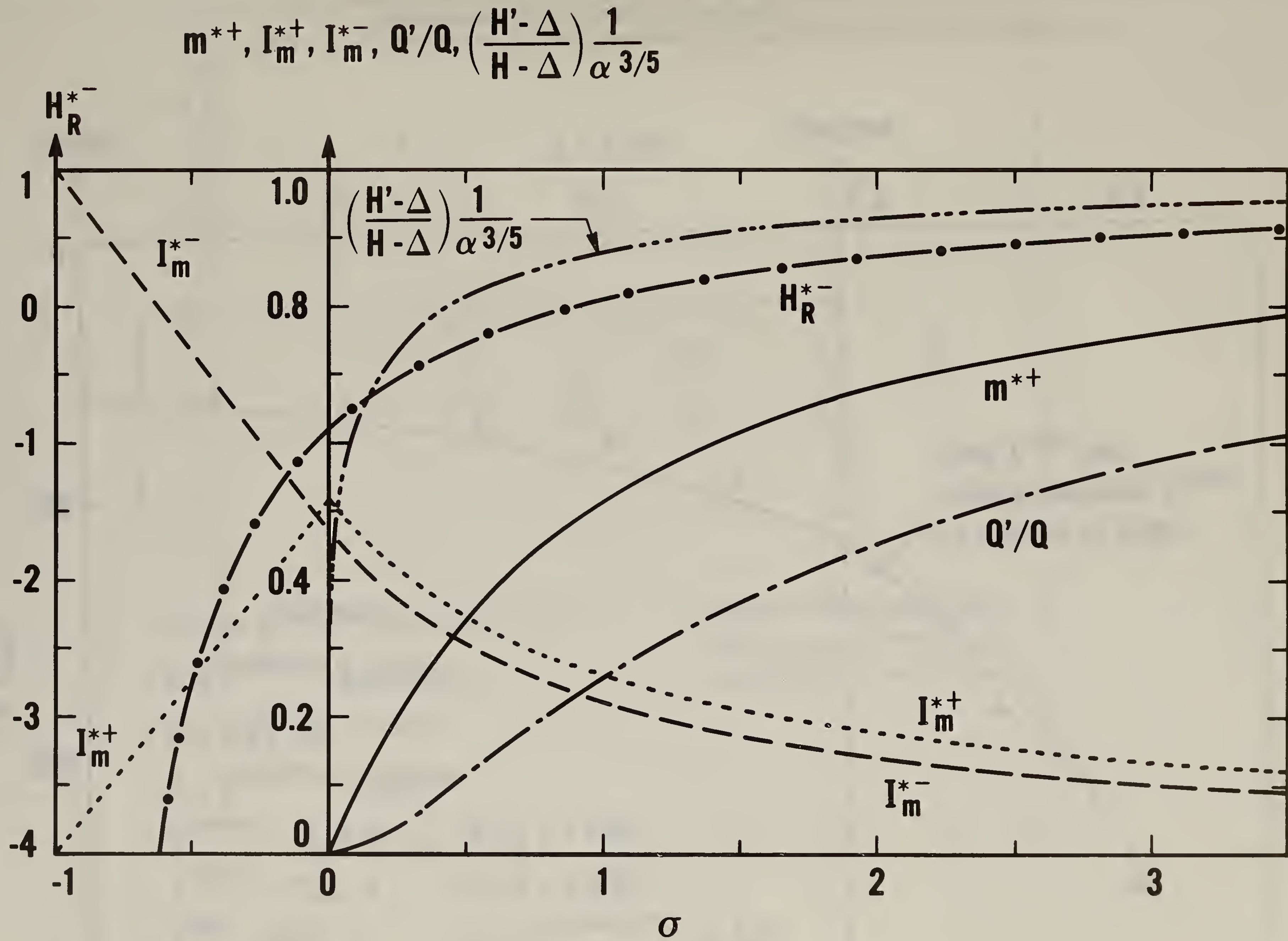

Figure 5. Plots of solutions to eqs. (25)-(32).

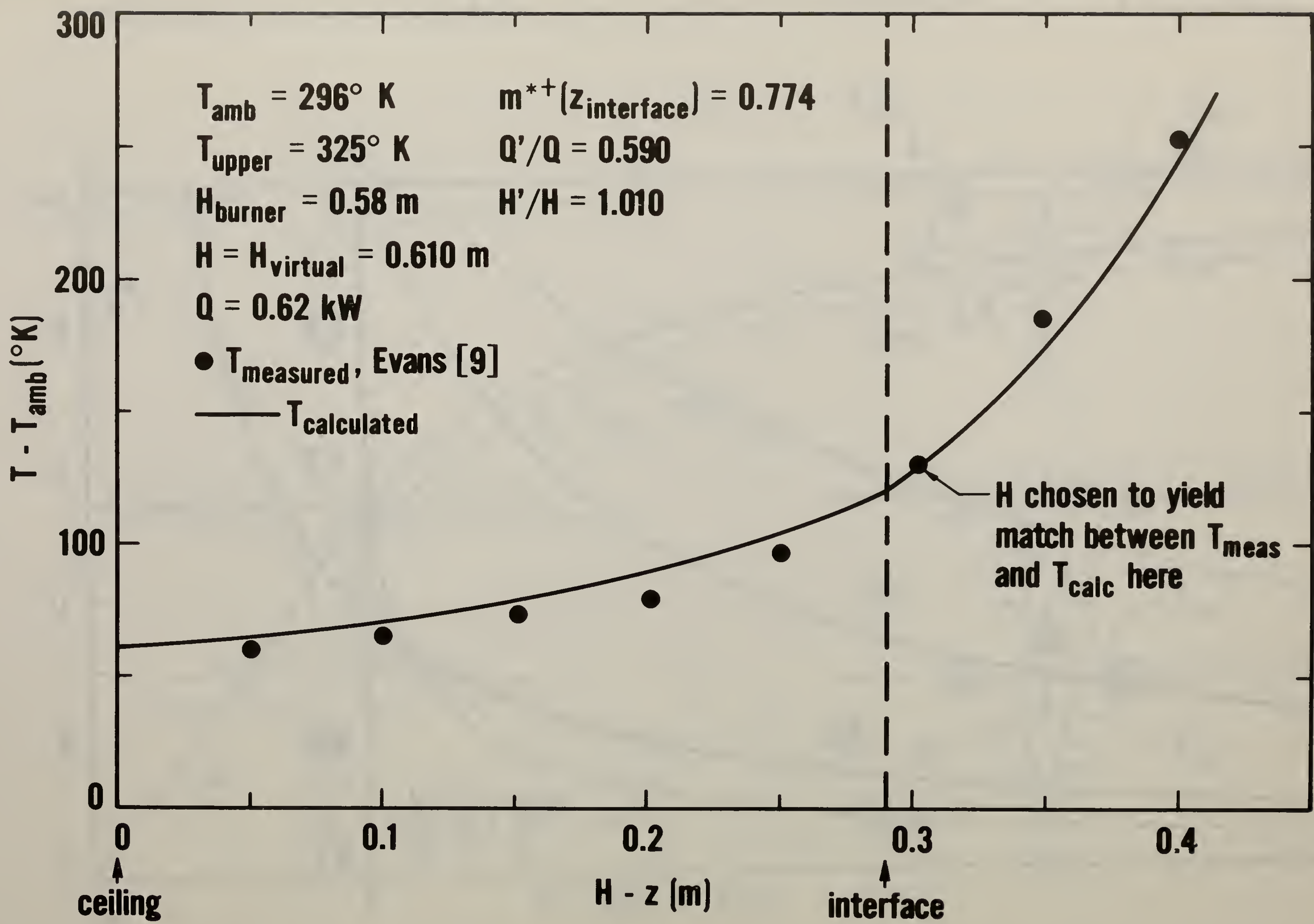

Figure 6. Comparisons between measured [9] and calculated plume centerline temperatures for a Figure 1 scenario.

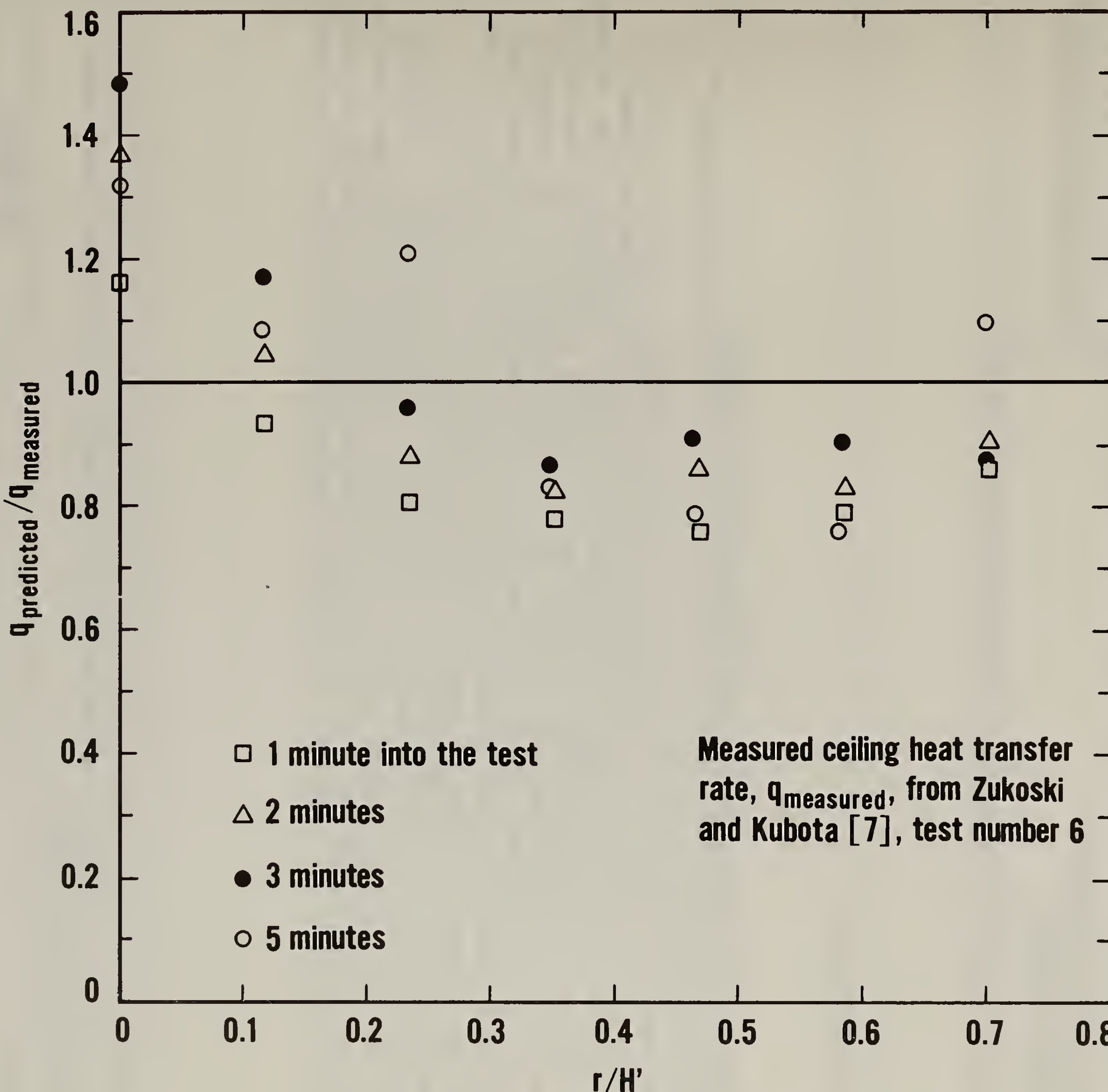

Figure 7. A comparison of predicted [7] and calculated ceiling heat transfer for a Figure 1 scenario.

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4. TITLE AND SUBTITLE

A Buoyant Source in the Lower of Two, Homogeneous, Stably Stratified Layers - A Problem of Fire in an Enclosure

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6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

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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)

A point source of buoyancy is located at a specified elevation within the lower of two homogeneous, stably stratified layers. A turbulent buoyant plume is formed above the source, and it impinges on the layers' interface. Depending on the strength of the source, its position below the interface and on the density difference of the two layers, it is conjectured that either: (1) a central portion of the impinging plume flow will penetrate and continue upward into the far field of the upper layer as a buoyant plume, the outer portion of the flow penetrating but then dropping down toward the interface because of negative relative buoyancy; or (2) none of the impinging plume flow will penetrate the upper layer (indepth) because of its being uniformly of negative relative buoyancy. Associated with these possible conditions will be an effective horizontal outflow of fluid at the interface. The paper derives and solves a set of model equations for these plume-interface interactions, and the results are applied to a generic heat transfer problem related to fires in enclosures.

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

Buoyant plumes; ceilings; compartment fires; fire models; fire plumes; heat transfer; mathematical models; smoke

13. AVAILABILITY

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