Analysis and modeling for a turbulent convective plume

D.N. Riahi

Department of Theoretical and Applied Mechanics

216 Talbot Laboratory, University of Illinois at Urbana-Champaign

104 S. Wright Street, Urbana, Illinois 61801 U.S.A.

Abstract

Asymptotic and scaling analyses are applied to develop a simple model for a turbulent convective plume at high Rayleigh number R in a high Prandtl number fluid layer whose lower boundary surface maintains steady local buoyant sources. The convective plume is assumed to be axisymmetric and conical and to have a radius b that is small compared with the depth of the layer. Under statistically steady conditions, to the leading order terms, the dependence of the mean components of axial velocity, radial velocity, pressure and temperature of the plume, as well as the vertical volume flux in the plume, on R and b is determined. The main results are in satisfactory agreement with available experimental observations. The results are equally applicable to the case where any finite number of such plumes are present under similar conditions, provided no interactions take place between the individual plumes.

1 Introduction

Plumes are buoyant jets, which arise due to steadily supplied buoyancy, and their buoyant motion is continuous between the source and any level in their domain [1]. There have been a number of theoretical, numerical and experimental studies of turbulent plumes and a collection of relevant references for such studies are given by Turner [1]. Morton et al. [2] developed, in particular, a simple model for plume maintained in a uniform or stably stratified ambient fluid, where the main assumptions were that the velocity and buoyancy force are constant across the plume and zero outside it, the rate of entrainment at the edge of the plume is proportional to some characteristic velocity at that height, the profiles of mean axial vertical velocity and mean buoyancy force in horizontal sections are of similar form at all heights, and the largest local variations of density are small in comparison with some chosen reference density. However, the governing equations that they used to build their model for the steady point source of the plumes involve only differentiation with respect to the axial variable z. These authors also carried out laboratory experiments on maintained plumes and compared their theoretical results to those due to their experiments. The experimental results show a more or less conical shape for the maintained plumes.

Telford [3,4,5] and Warner and Telford [6] investigated convective plumes with particular interest in the atmospheric plumes applications, but again the radial r variations of the dependent variables are not taken into account. Telford [3] studied an isolated plume in still air, under the assumptions that the plume is uniform over all the horizontal section, turbulent energy dissipation is zero, turbulent energy spectrum is not taken into account, vertical mixing is negligible and wind shear is zero. Warner and Telford [6] studied the observations made from the ground and from aircraft and concluded that clear air thermals (suddenly released buoyant elements [1]) are continuing plumes, they rise through a neutral to slightly stably stratified environment, flow within and outside the plumes are turbulence, and mixing into and out of the plumes take place. They then found that the real plumes in the atmosphere have little resemblance to most existing models. Telford [4] extended his earlier theory [3] to provide a theory of rising and descending air in a field of plumes, where the effect of time dependent heating during day-night cycle was taken into account. Telford [4] ignored wind stress and assumed each plume is immersed in the turbulent downdraft which comprises the return flow. He suggested that his extended theory could lead to a prediction of the onset of a different form of convection resulting from instabilities in the convection layer. Telford [5] generalized his earlier dimensional type solutions [3,4] by non-dimensionalizing the original equations that provided such solutions.

More recently Offut [7] carried out experimental investigation of turbulent thermal convection in a horizontal layer of fluid with Prandtl number about 7.35 using particle image velocimetry and shadowgraph visualization. The Rayleigh number R was about 10^8. In regard to the convective plumes, he obtained, in particular, the following results. The fluid layer was densely populated with viscous, mushroom-headed plumes. The plume geometry was characterized typically by a thin stem 2-3 m.m. wide, non-dimensional radius b of the plume's cross section was about 0.05 to 0.5 for a non-dimensional unity of the layer thickness, and a mushroom shaped cap, which grew in width as the plume ascended. The stems grew very little in width as the plumes rose, while the caps grew from several m.m. across at the level very close to the lower boundary of the layer to 3-4 c.m. near the top boundary of the layer. However, plumes' interactions or merging problem was difficult to be observed and is presently unresolved.

In the present paper we have developed a more realistic theoretical model for a maintained plume which can also be used for a field of such plumes under similar conditions. The model obeys the Navier-Stokes and continuity equations subjected to the Boussinesq approximation and under a number of realistic assumptions and conditions some of which have been used in the previous models described before. The full assumptions and conditions, underwhich such model is built, are given in the next section.

2 Formulation

We consider a thin horizontal layer of high viscous fluid and of thickness d above a heated horizontal surface. The gravity vector is assumed to be in the downward direction perpendicular to the direction of the surface and anti-parallel to the vertical z-axis. We assume that there are steady maintained plumes initiated at discrete locations on the surface. These plumes with steady point sources are assumed to have similar shapes and to be subjected to similar conditions. Since we will be concerned mainly with convection in any conical type shape plume [2], whose axis is assumed to be parallel to the z-axis, within the horizontal fluid layer, we consider the governing Navier-Stokes, continuity and temperature equations, under the so-called Boussinesq approximation [1], in a cylindrical coordinate whose axial direction is along the z-axis. We assume that the temperature difference across the layer is sufficiently high and the fluid in the layer, both inside and outside the plumes, is in turbulent motion. We shall consider mean time averaged axisymmetric convection in a conical plume, whose apex and axis coincides with the origin 0 and the z-axis of the coordinate system, respectively, and in the fluid layer in the asymptotic limit of strong buoyancy force, due to the vertical temperature gradient, and sufficiently large Prandtl number $P_r = \nu/K$. Hereν is the kinematic viscosity and K is the sum of eddy and molecular thermal diffusivity.

The non-dimensional form of the equations for the momentum, continuity and temperature for the statistically steady mean flow component of the fluid in the plume are then

$$\nabla^2 \boldsymbol{u} = R(\nabla P + \theta \hat{z}), \tag{1.1}$$

$$\nabla \cdot \boldsymbol{u} = 0, \tag{1.2}$$

$$\nabla^2 \theta = \boldsymbol{u} \cdot \nabla \theta, \tag{1.3}$$

where $\boldsymbol{u} = u\hat{r} + w\hat{z}$ is the mean velocity vector, u is the radial component of the mean velocity, $\hat{r}$ is a unit vector in the direction of the radial r-axis, w is the axial component of $\boldsymbol{u}, \hat{z}$ is a unit vector in the direction of the axial z-axis, p is the mean pressure, θ is the mean temperature, $R = \beta \Delta T g d^3/(K\nu)$ is the Rayleigh number, β is the coefficient of thermal expansion, ΔT is the temperature difference imposed across the layer, and g is acceleration due to gravity.

The boundary conditions for the flow within the plume and outside are

$$\boldsymbol{u} = \theta - 1 = 0 \quad \text{at} \quad z = 0, \tag{1.4}$$

$$\hat{z} \cdot \boldsymbol{u} = \theta = 0 \quad \text{at} \quad z = 1, \tag{1.5}$$

where it is assumed that the fluid layer is bounded above by a horizontal free surface at $z = 1$.

It is seen from the governing equations (1.1)-(1.3) that, in contrast to the previous models, the radial rate of change of the dependent variables are taken into account. In the next section we shall apply asymptotic and scaling analyses for (1.1)-(1.5), in the asymptotic limit of sufficiently large R, to determine the strongly nonlinear statistically steady state and axisymmetric behavior of the mean flow in the layer and mainly mean turbulent convection features in each plume for sufficiently large P_r. Extension to arbitrary P_r for convection with non-axisymmetric behavior is planned to be done by the present author in near future. It should be noted that no analyses of the plumes' interactions or merging will be done in the present paper. However, mixing on the plume's boundary will be taken care of due to entrainment modeling [2] which will be described in the next section.

3 Analysis and results

Let us designate $b(z)$ to be the radius of the horizontal cross section of a plume under consideration whose axis coincides with the z-axis. It is assumed that b is small ($b << 1$) [7]. We assume that the orders of magnitude of r and z are, respectively b and 1. Assuming $|\boldsymbol{u}|$ in the plumes is much larger than the corresponding one outside the plumes, then (1.1) implies that to the leading terms pressure field is unaffected by the flow velocity everywhere and θ is independent of r. The governing equations (1.1) and (1.3) then imply that $p = p_0(z), w = \tilde{w}_0(z)$ and $\theta = \theta_0(z)$ at most, where $p_0, \tilde{w}_0$ and θ_0 are the leading order terms for p, w and θ, respectively, and satisfy the following equations

$$\frac{dP_0}{dz} + \theta_0 = 0, \tag{2.1}$$

$$\tilde{w}_0 \frac{d\theta_0}{dz} = \frac{d^2\theta_0}{dz^2}. \tag{2.2}$$

Here $\tilde{w}_0$ is leading order term for the downward axial velocity for the flow outside the plumes. Let us now introduce a stream function $\psi(r, z)$ for the flow, so that

$$(u, w) = \left(-\frac{1}{r}\frac{\partial \psi}{\partial z}, \frac{1}{r}\frac{\partial \psi}{\partial r} \right). \tag{3}$$

Using (1.2) and (6), we have $\psi \sim bu \sim b^2 w$. Using these results, (1.3) yield

$$\frac{\partial}{\partial r}\left(r\frac{\partial \theta_1}{\partial r} \right) = \frac{\partial \psi}{\partial r}\frac{d\theta_0}{dz}, \tag{4}$$

where $\theta_1(r, z)$ is the deviation of θ from θ_0, and it is assumed that $\theta_1 << \theta_0$. Integrating (4) twice with respect to r and assuming mean flow solution with closed streamlines, we find

$$\theta_1 \sim \psi(b, z)\frac{d\theta_0}{dz} \ln r, \tag{5.1}$$

where

$$2\pi\psi(b, z) = \int_0^b 2\pi r w dr \tag{5.2}$$

is the vertical volume flux in the plume.

Using (3), we have

$$u \sim -\frac{\partial \psi(b, z)}{\partial z}\left(\frac{1}{r} \right) \quad \text{as} \quad r \to b. \tag{6}$$

Considering the radial component of (1.1), we have to the leading terms

$$\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r} \right) = rR\frac{\partial P}{\partial r}, \tag{7}$$

Near the wall of the plume, use (6) in (7) and then integrate the resulting equation to find

$$\Delta P \sim \frac{\partial \psi(b,z)}{\partial z} \left(\frac{1}{2b^2 R} \right), \tag{8}$$

where ∇P represents the pressure near the wall of the plume.

Considering the axial component of (1.1), we have to the leading terms

$$\frac{\partial}{\partial r} \left(r \frac{\partial w}{\partial r} \right) = rR\theta_1. \tag{9}$$

Using (5.1) in (9) and integrating the resulting equation in r for w, we find

$$w \sim \left(\frac{b^2 R}{r} \right) \psi(b,z) \frac{d\theta_0}{dz} \left(\ln b - 1 \right), \tag{10}$$

which holds near the wall of the plume. Using (6), (10) and the continuity constraint (1.2), we find

$$\frac{d\theta_0}{dz} Rb^4 \ln b \sim 1. \tag{11}$$

from (6) and (10) near the wall of the plume, it is seen that the wall of the plume should be inclined with respect to z-axis as is consistently assumed.

Now denote u_0 to be the leading order term for u. The equations (2.1)-(2.2), derived from the axial component of (1.1) and from (1.3), together with the equation

$$\frac{\partial}{\partial r}(ru_0) = -r\frac{\partial w_0}{\partial z}, \tag{12}$$

derived from (1.2), subjected to the boundary conditions

$$u_0 = w_0 = \theta_0 - 1 = 0 \quad \text{at} \quad z = 0, \tag{13.1}$$

$$w_0 = \theta_0 = 0 \quad \text{at} \quad z = 1, \tag{13.2}$$

derived from (1.4)-(1.5), can be solved in principle if the expression for w_0, which is the leading order term for w in the plume, was known or if w_0 was given in terms of an equation involving any one or more of these dependent variables. However, the expression for w_0 is not yet known and there is no additional equation for w_0. The radial component of (1.1) is not of much help here since its leading form,

$$\frac{\partial}{\partial r}\left(r\frac{\partial u_0}{\partial r}\right) = rR\frac{\partial(P-P_0)}{\partial r}, \tag{14}$$

involves the deviation of P from P_0 which serves as additional unknown. To determine w_0, we proceed in the following way described in the next paragraph.

In order to determine the expression for w_0 on the boundary of the plume, we make use of (10)-(11) to the leading term to obtain

$$4w_0 = \psi(b,z)/b^2 \quad \text{as} \quad r \to b. \tag{15}$$

Thus, the expression for $w_0(b,z)$ will be known once the expression for $\psi(r,z)$ is evaluated at $r = b$. We use a Polhausen type method [8] suggested by Lighthill [9] to determine ψ. The boundary conditions to be satisfied by ψ are

$$\psi = 0 \quad \text{at} \quad r = 0, \tag{16.1}$$

$$\frac{\partial}{\partial z}\left(b^2\frac{\partial\psi}{\partial r}\right) = 2b\alpha\frac{\partial\psi}{\partial r} \quad \text{at} \quad r = b, \tag{16.2}$$

where (16.2) relates the inflow velocity at the edge of the plume to the vertical velocity within the plume and involves an entrainment constant parameter α [1,2]. We now introduce a trial function for

$$(\theta - 1 + z) = (\theta_0 - 1 + z)T(S), \tag{17}$$

where $S = r/b$ and $T(S)$ is a polynomial in S. The boundary conditions

$$\frac{\partial\theta}{\partial r} = 0 \quad \text{at} \quad r = 0, \tag{18.1}$$

$$\theta - \theta_0 = \frac{\partial\theta}{\partial r} = 0 \quad \text{at} \quad r = b, \tag{18.2}$$

chosen for θ, then leads to the following conditions for T(S)

$$\frac{dT}{dS} = 0 \quad \text{at} \quad S = 0, \tag{19.1}$$

$$T - 1 = \frac{dT}{dS} = 0 \quad \text{at} \quad S = 1. \tag{19.2}$$

A candidate for T(S) satisfying (19.1)-(19.2) is

$$T(S) = S^3 - \frac{3}{2}S^2 + \frac{3}{2}. \tag{20}$$

Using (3), (17) and (20) in (9), we find

$$\frac{1}{S}\frac{\partial}{\partial S}\left[S\frac{\partial}{\partial S}\left(\frac{1}{S}\frac{\partial\psi}{\partial S}\right)\right] = b^4 R(\theta_0 - 1 + z)\left(S^3 - \frac{3}{2}S^2 + \frac{1}{2}\right). \tag{21}$$

Integrating (21) with respect to S three times and making use of (16.1)-(16.2) and the finiteness value of the vertical velocity at $S = 0$, we find

$$\psi = b^4 R(\theta_0 - 1 + z)\left(\frac{1}{175}S^7 - \frac{1}{64}S^6 + \frac{1}{32}S^4 + CS^2\right), \tag{22.1}$$

where

$$C = \left[60(\theta_0 - 1 + z)\frac{db}{dz} + 114\alpha(\theta_0 - 1 + z) - 57b\left(\frac{d\theta_0}{dz} + 1\right)\right] / \left[1600b\left(\frac{d\theta_0}{dz} + 1\right) - 3200\alpha(\theta_0 - 1 + z)\right]. \tag{22.2}$$

Using (1.4)-(1.5), (2.1)-(2.2) and (22.1)-(22.2), we find the following results to the leading order terms:

$$2\pi\psi(b, z) = 2\pi b^4 R\phi\left[\frac{239}{11200} + \frac{\left(60\phi\frac{db}{dz} + 114\alpha\phi - 57\frac{d\phi}{dz}b\right)}{1600\left(\frac{d\phi}{dz}b - 2\alpha\phi\right)}\right], \tag{23.1}$$

$$P_0(z) = \int_0^z (\phi + 1 - z)dz, \tag{23.2}$$

$$\frac{d^2\phi}{dz^2} = -2\pi\psi(b,z)N\left(\frac{d\phi}{dz} - 1\right), \tag{23.3}$$

$$\phi = 0 \quad \text{at} \quad z = 0, 1, \tag{23.4}$$

where

$$\phi = \theta_0(z) - 1 + z, \tag{23.5}$$

N is the number density of all the plumes in the fluid layer and (23.1) represents total vertical volume flux in the plume.

The solution to (23.3)-(23.4) was determined numerically using a shooting type iterations, and then the vertical volume flux in the plume is determined from (23.1). The results for θ_0 and $2\pi\psi(b, z)$ are determined fro $N = 10$, which is close to the observation in [7], and

$$b(z) = 0.01z + 0.02 \tag{24}$$

and for two different values of R. Talbe 1 presents these results for different z values across the fluid layer. It is seen from these results that the leading order temperature and the volume flux within the plume increase with R. At the bottom and top boundaries ϕ and $2\pi\psi$ are zero as (23.4)-(23.5) also indicate. Thus very close to the upper boundary the vertical volume flux decreases rapidly and the flow is mainly in the radial (horizontal) direction.

In relation of the present results to those available experimental results, it is of interest to refer to offut [7] observational and experimental results regarding the plumes in the Rayleigh-Benard type system. Offut [7] investigated experimentally turbulent thermal convection in a horizontal layer of water ($P_r = 7.35$) of depth 10 cm and at $R = 10^8$. He observed the layer was densely populated with plumes. He characterized a hot plume geometry by a thin stem 2-3 mm wide and a mushroom shaped cap, which grew in width as the hot plume rose. Upon reaching the upper fourth of the layer, the plumes spread out horizontally and stagnated before diffusing away. Plumes moved upward with an initial vertical velocity that was a fraction of their terminal velocity. Plumes, interactions or merging was difficult to be observed with the shadowgraph technique employed. For $R = 10^8$, about 32 particular plumes were used to determine the mean cap vertical speed which was found to be about 0.61 cm/s. In the present theoretical studies, we used the relation (11) and the numerical finding that $|\frac{d\theta_0}{dz}|$ is close to unity to find that dimensional value of b at $R = 10^8$ is about 0.5 mm. This result is in satisfactory agreement with observation reported in [7] despite the fact that infinite Prandtl number and steady axisymmetric conditions are employed here. Next, using the present result presented in table 1 for $R = 10^8$, we determined the dimensional value of the vertical velocity in the plume at $z = 0.9$ to be about 0.39cm. This result is also in satisfactory agreement with the corresponding experimental one reported in [7].

It should be noted that the present asymptotic limit of large R taken in the analysis did not allow N to be too large, and the acceptable order of magnitude of $\tilde{w}_0$ implies that

$$N_{\max} = O\left[\frac{1}{\int_0^1 \psi(b,z)dz}\right], \tag{25}$$

where $N_{\max}$is the maximum allowed value of N. Hence the value of N chosen in the present study is reasonable.

4 Some conclusions

(i). The radius of the plume is of the order of $(R\ln R)^{\frac{-1}{4}}$ and its value is in satisfactory agreement with the experimental observation [7].

(ii). Both vertical velocity and temperature in the plume increase with R.

(iii). The value of the vertical velocity in the plume is in satisfactory agreement with the experimental result [7].

(iv). The vertical volume flux in the plume increases with R. It also increases with z up to a value of vertical level close to the upper boundary beyond which it decreases rapidly. This result is also in agreement with the experimental observation [7] that the plumes spread out horizontally upon reaching the upper fourth of the layer.

References

[1] Turner, J.S.: Buoyancy effects in fluids. Cambridge University Press (1973).

[2] Morton, B.R., Taylor, G.I., Turner, J.S.: Turbulent gravitational convection from maintained and instantaneous sources.*Proc. Royal Soc. London* **A234**, 1-23 (1956).

[3] Telford, J.W.: The convective mechanism in clear air. *J. Atmospheric Sciences* **23**, 652-666 (1967).

[4] Telford, J.W.: Convective plumes in a convective field. *J. Atmospheric Sciences* **27**, 347-358 (1970).

[5] Telford, J.W.: A plume theory for the convective field in clear air. *J. Atmospheric Sciences* **29**, 128-134 (1972).

[6] Warner, J. and Telford, J.W.: Convection below cloud base. *J. Atmospheric Sciences* **24**, 374-382 (1967).

[7] Offut, P.W.: Development of experimental techniques and studies of spatial structure in turbulent thermal convection. Ph.D. Thesis, Department of Theoretical and Applied Mech., UIUC (1995).

[8] Schlichting, H.: Boundary Layer Theory, Seventh Ed. McGraw-Hill Book Co. (1979).

[9] Lighthill, M.J.: Theoretical considerations on free convection in tubes. *Quarterly J. Mech. and Appl. Maths.* **6**, 398-439 (1953).

z	$R = 10^7$		$R = 10^8$	
	$\theta_0(z)$	$2\pi\psi(b, z)$	$\theta_0(z)$	$2\pi\psi(b, z)$
0.0	1.0000	0.0000	1.0000	0.0000
0.1	0.9002	0.0001	0.9002	0.0006
0.2	0.8004	0.0004	0.8004	0.0028
0.3	0.7006	0.0012	0.7010	0.0076
0.4	0.6010	0.0024	0.6024	0.0200
0.5	0.5016	0.0044	0.5058	0.0536
0.6	0.4026	0.0082	0.4147	0.1473
0.7	0.3045	0.0156	0.3371	0.4317
0.8	0.2076	0.0299	0.2883	1.5438
0.9	0.1143	0.0582	0.2776	7.5108
1.0	0.0000	0.0000	0.0000	0.0000

Table 1: θ_0 and $2\pi\psi(b, z)$

versus z for $R = 10^7$ and 10^8.

List of Recent TAM Reports

No.	Authors	Title	Date
786	Riahi, D. N.	Finite bandwidth, long wavelength convection with boundary imperfections: Near-resonant wavelength excitation—*International Journal of Mathematics and Mathematical Sciences* **21**, 171–182 (1997)	Mar. 1995
787	Turner, J. A., and R. L. Weaver	Average response of an infinite plate on a random foundation—*Journal of the Acoustical Society of America* **99**, 2167–2175 (1996)	Mar. 1995
788	Weaver, R. L., and D. Sornette	The range of spectral correlations in pseudointegrable systems: GOE statistics in a rectangular membrane with a point scatterer—*Physical Review E* **52**, 341 (1995)	Apr. 1995
789	Students in TAM 293–294	Thirty-second student symposium on engineering mechanics, J. W. Phillips, coordinator: Selected senior projects by K. F. Anderson, M. B. Bishop, B. C. Case, S. R. McFarlin, J. M. Nowakowski, D. W. Peterson, C. V. Robertson, and C. E. Tsoukatos	Apr. 1995
790	Figa, J., and C. J. Lawrence	Linear stability analysis of a gravity-driven Newtonian coating flow on a planar incline	May 1995
791	Figa, J., and C. J. Lawrence	Linear stability analysis of a gravity-driven viscosity-stratified Newtonian coating flow on a planar incline	May 1995
792	Cherukuri, H. P., and T. G. Shawki	On shear band nucleation and the finite propagation speed of thermal disturbances—*International Journal of Solids and Structures,* in press (1996)	May 1995
793	Harris, J. G.	Modeling scanned acoustic imaging of defects at solid interfaces—Chapter in *IMA Workshop on Inverse Problems in Wave Propagation,* eds. G. Chevant, G. Papanicolaou, P. Sacks and W. E. Symes, 237–258, Springer-Verlag, New York (1996)	May 1995
794	Sottos, N. R., J. M. Ockers, and M. J. Swindeman	Thermoelastic properties of plain weave composites for multilayer circuit board applications	May 1995
795	Aref, H., and M. A. Stremler	On the motion of three point vortices in a periodic strip—*Journal of Fluid Mechanics* **314**, 1–25 (1996)	June 1995
796	Barenblatt, G. I., and N. Goldenfeld	Does fully-developed turbulence exist? Reynolds number independence versus asymptotic covariance—*Physics of Fluids* **7**, 3078–3082 (1995)	June 1995
797	Aslam, T. D., J. B. Bdzil, and D. S. Stewart	Level set methods applied to modeling detonation shock dynamics—*Journal of Computational Physics,* **126**, 390–409 (1996)	June 1995
798	Nimmagadda, P. B. R., and P. Sofronis	The effect of interface slip and diffusion on the creep strength of fiber and particulate composite materials—Proceedings of the ASME Applied Mechanics Division **213**, 125–143 (1995)	July 1995
799	Hsia, K. J., T.-L. Zhang, and D. F. Socie	Effect of crack surface morphology on the fracture behavior under mixed mode loading—*ASTM Special Technical Publication* 1296, in press (1996)	July 1995
800	Adrian, R. J.	Stochastic estimation of the structure of turbulent fields—*Eddy Structure Identification*, ed. J. P. Bonnet, Springer: Berlin 145–196 (1996)	Aug. 1995
801	Riahi, D. N.	Perturbation analysis and modeling for stratified turbulence	Aug. 1995
802	Thoroddsen, S. T.	Conditional sampling of dissipation in high Reynolds number turbulence—*Physics of Fluids* **8**, 1333–1335	Aug. 1995
803	Riahi, D. N.	On the structure of an unsteady convecting mushy layer—*Acta Mechanica*, in press (1996)	Aug. 1995
804	Meleshko, V. V.	Equilibrium of an elastic rectangle: The Mathieu–Inglis–Pickett solution revisited—*Journal of Elasticity* **40**, 207–238 (1995)	Aug. 1995
805	Jonnalagadda, K., G. E. Kline, and N. R. Sottos	Local displacements and load transfer in shape memory alloy composites	Aug. 1995

No.	*Authors*	*Title*	*Date*
806	Nimmagadda, P. B. R., and P. Sofronis	On the calculation of the matrix–reinforcement interface diffusion coefficient in composite materials at high temperatures—*Acta Metallurgica et Materialia*, **44**, 2711–2716 (1996)	Aug. 1995
807	Carlson, D. E., and D. A. Tortorelli	On hyperelasticity with internal constraints—*Journal of Elasticity* **42**, 91–98 (1966)	Aug. 1995
808	Sayre, T. L., and D. N. Riahi	Oscillatory instabilities of the liquid and mushy layers during solidification of alloys under rotational constraint—*Acta Mechanica* **121** , 143–152 (1997)	Sept. 1995
809	Xin, Y.-B., and K. J. Hsia	Simulation of the brittle–ductile transition in silicon single crystals using dislocation mechanics	Oct. 1995
810	Ulysse, P., and R. E. Johnson	A plane-strain upper-bound analysis of unsymmetrical single-hole and multi-hole extrusion processes	Oct. 1995
811	Fried, E.	Continua described by a microstructural field—*Zeitschrift für angewandte Mathematik und Physik*, **47**, 168–175 (1996)	Nov. 1995
812	Mittal, R., and S. Balachandar	Autogeneration of three-dimensional vortical structures in the near wake of a circular cylinder	Nov. 1995
813	Segev, R., E. Fried, and G. de Botton	Force theory for multiphase bodies—*Journal of Geometry and Physics*, in press (1996)	Dec. 1995
814	Weaver, R. L.	The effect of an undamped finite-degree-of-freedom "fuzzy" substructure: Numerical solutions and theoretical discussion—*Journal of the Acoustical Society of America* **100**, 3159–3164 (1996)	Jan. 1996
815	Haber, R. B., C. S. Jog, and M. P. Bendsøe	A new approach to variable-topology shape design using a constraint on perimeter—*Structural Optimization* **11**, 1–12 (1996)	Feb. 1996
816	Xu, Z.-Q., and K. J. Hsia	A numerical solution of a surface crack under cyclic hydraulic pressure loading	Mar. 1996
817	Adrian, R. J.	Bibliography of particle velocimetry using imaging methods: 1917–1995—*Produced and distributed in cooperation with TSI, Inc., St. Paul, Minn.*	Mar. 1996
818	Fried, E., and G. Grach	An order-parameter based theory as a regularization of a sharp-interface theory for solid–solid phase transitions—*Archive for Rational Mechanics and Analysis*, in press (1996)	Mar. 1996
819	Vonderwell, M. P., and D. N. Riahi	Resonant instability mode triads in the compressible boundary-layer flow over a swept wing—*International Journal of Engineering Science*, in press (1997)	Mar. 1996
820	Short, M., and D. S. Stewart	Low-frequency two-dimensional linear instability of plane detonation—*Journal of Fluid Mechanics*, in press (1997)	Mar. 1996
821	Casagranda, A., and P. Sofronis	On the scaling laws for the consolidation of nanocrystalline powder compacts—Proceedings of the IUTAM Symposium on the Mechanics of Granular and Porous Materials (1996)	Apr. 1996
822	Xu, S., and D. S. Stewart	Deflagration-to-detonation transition in porous energetic materials: A comparative model study—*Journal of Fluid Mechanics*, in press (1997)	Apr. 1996
823	Weaver, R. L.	Mean and mean-square responses of a prototypical master/fuzzy structure—*Journal of the Acoustical Society of America*, in press (1996)	Apr. 1996
824	Fried, E.	Correspondence between a phase-field theory and a sharp-interface theory for crystal growth—*Continuum Mechanics and Thermodynamics*, in press (1997)	Apr. 1996
825	Students in TAM 293–294	Thirty-third student symposium on engineering mechanics, J. W. Phillips, coordinator: Selected senior projects by W. J. Fortino II, A. A. Mordock, and M. R. Sawicki	May 1995
826	Riahi, D. N.	Effects of roughness on nonlinear stationary vortices in rotating disk flows—*Mathematical and Computer Modeling*, in press (1996)	June 1996
827	Riahi, D. N.	Nonlinear instabilities of shear flows over rough walls	June 1996
828	Weaver, R. L.	Multiple scattering theory for a plate with sprung masses: Mean and mean-square responses	July 1996

List of Recent TAM Reports (cont'd)

No.	*Authors*	*Title*	*Date*
829	Moser, R. D., M. M. Rogers, and D. W. Ewing	Self-similarity of time-evolving plane wakes	July 1996
830	Lufrano, J. M., and P. Sofronis	Enhanced hydrogen concentrations ahead of rounded notches and cracks—Competition between plastic strain and hydrostatic constraint	July 1996
831	Riahi, D. N.	Effects of surface corrugation on primary instability modes in wall-bounded shear flows	Aug. 1996
832	Bechel, V. T., and N. R. Sottos	Measuring debond length in the fiber pushout test—Proceedings of the ASME Mechanics and Materials Conference (1996)	Aug. 1996
833	Riahi, D. N.	Effect of centrifugal and Coriolis forces on chimney convection during alloy solidification—*Journal of Crystal Growth* **179**, 287–296 (1997)	Sept. 1996
834	Cermelli, P., and E. Fried	The influence of inertia on configurational forces in a deformable solid—*Proceedings of the Royal Society of London A*, in press (1996)	Oct. 1996
835	Riahi, D. N.	On the stability of shear flows with combined temporal and spatial imperfections	Oct. 1996
836	Carranza, F. L., B. Fang, and R. B. Haber	An adaptive space–time finite element model for oxidation-driven fracture	Nov. 1996
837	Carranza, F. L., B. Fang, and R. B. Haber	A moving cohesive interface model for fracture in creeping materials	Nov. 1996
838	Balachandar, S., R. Mittal, and F. M. Najjar	Properties of the mean wake recirculation region in two-dimensional bluff body wakes—*Journal of Fluid Mechanics*, in press (1997)	Dec. 1996
839	Ti, B. W., W. D. O'Brien, Jr., and J. G. Harris	Measurements of coupled Rayleigh wave propagation in an elastic plate	Dec. 1996
840	Phillips, W. R. C.	On finite-amplitude rotational waves in viscous shear flows	Jan. 1997
841	Riahi, D. N.	Direct resonance analysis and modeling for a turbulent boundary layer over a corrugated surface—*Acta Mechanica*, in press (1998)	Jan. 1997
842	Liu, Z.-C., R. J. Adrian, C. D. Meinhart, and W. Lai	Structure of a turbulent boundary layer using a stereoscopic, large format video-PIV	Jan. 1997
843	Fang, B., F. L. Carranza, and R. B. Haber	An adaptive discontinuous Galerkin methods for viscoplastic analysis	Jan. 1997
844	Xu, S., T. D. Aslam, and D. S. Stewart	High-resolution numerical simulation of ideal and non-ideal compressible reacting flows with embedded internal boundaries	Jan. 1997
845	Zhou, J., C. D. Meinhart, S. Balachandar, and R. J. Adrian	Formation of coherent hairpin packets in wall turbulence	Feb. 1997
846	Lufrano, J. M., P. Sofronis, and H. K. Birnbaum	Elastoplastically accommodated hydride formation and embrittlement	Feb. 1997
847	Keane, R. D., N. Fujisawa, and R. J. Adrian	Unsteady non-penetrative thermal convection from non-uniform surfaces	Feb. 1997
848	Aref, H., and M. Brøns	On stagnation points and streamline topology in vortex flows	Mar. 1997
849	Asghar, S., T. Hayat, and J. G. Harris	Diffraction by a slit in an infinite porous barrier	Mar. 1997
850	Shawki, T. G., H. Aref, and J. W. Phillips	Mechanics on the Web—Proceedings of the International Conference on Engineering Education (Aug. 1997, Chicago)	Apr. 1997

No.	*Authors*	*Title*	*Date*
851	Stewart, D. S., and J. Yao	The normal detonation shock velocity–curvature relationship for materials with non-ideal equation of state and multiple turning points	Apr. 1997
852	Fried, E., A. Q. Shen, and S. T. Thoroddsen	Traveling waves, standing waves, and cellular patterns in a steadily forced granular medium	Apr. 1997
853	Boyland, P. L., H. Aref, and M. A. Stremler	Topological fluid mechanics of stirring	Apr. 1997
854	Parker, S. J., and S. Balachandar	Viscous and inviscid instabilities of flow along a streamwise corner	May 1997
855	Soloff, S. M., R. J. Adrian, and Z.-C. Liu	Distortion compensation for generalized stereoscopic particle image velocimetry—*Measurement Science and Technology* 8, 1–14 (1997)	May 1997
856	Zhou, Z., R. J. Adrian, S. Balachandar, and T. M. Kendall	Mechanisms for generating coherent packets of hairpin vortices in near-wall turbulence	June 1997
857	Neishtadt, A. I., D. L. Vainshtein, and A. A. Vasiliev	Chaotic advection in a cubic Stokes flow	June 1997
858	Weaver, R. L.	Ultrasonics in an aluminum foam	July 1997
859	Riahi, D. N.	High gravity convection in a mushy layer during alloy solidification	July 1997
860	Najjar, F. M., and S. Balachandar	Low-frequency unsteadiness in the wake of a normal flat plate	Aug. 1997
861	Short, M.	A parabolic linear evolution equation for cellular detonation instability	Aug. 1997
862	Short, M., and D. S. Stewart	Cellular detonation stability—I: A normal-mode linear analysis	Sept. 1997
863	Carranza, F. L., and R. B. Haber	A numerical study of intergranular fracture and oxygen embrittlement in an elastic–viscoplastic solid	Oct. 1997
864	Sakakibara, J., and R. J. Adrian	Whole-field measurement of temperature in water using two-color laser-induced fluorescence	Oct. 1997
865	Riahi, D. N.	Effect of surface corrugation on convection in a three-dimensional finite box of fluid-saturated porous material	Oct. 1997
866	Baker, C. F., and D. N. Riahi	Three-dimensional flow instabilities during alloy solidification	Oct. 1997
867	Fried, E.	Introduction (only) to *The Physical and Mathematical Foundations of the Continuum Theory of Evolving Phase Interfaces* (book containing 14 seminal papers dedicated to Morton E. Gurtin)	Oct. 1997
868	Folguera, A., and J. G. Harris	Coupled Rayleigh surface waves in a slowly varying elastic waveguide	Oct. 1997
869	Stewart, D. S.	Detonation shock dynamics: Application for precision cutting of metal with detonation waves	Oct. 1997
870	Shrotriya, P., and N. R. Sottos	Creep and relaxation behavior of woven glass/epoxy substrates for multilayer circuit board applications	Nov. 1997
871	Riahi, D. N.	Boundary wave–vortex interaction in channel flow at high Reynolds numbers	Nov. 1997
872	George, W. K., L. Castillo, and M. Wosnik	A theory for turbulent pipe and channel flows	Nov. 1997
873	Aslam, T. D., and D. S. Stewart	Detonation shock dynamics and comparisons with direct numerical simulation	Dec. 1997
874	Short, M., and A. K. Kapila	Blow-up in semilinear parabolic equations with weak diffusion	Dec. 1997
875	Riahi, D. N.	Analysis and modeling for a turbulent convective plume	Jan. 1998