Int. J. Heat Mass Transfer. Vol. 28, No. 4, pp. 771–777, 1985
Printed in Great Britain

0017-9310/85 $3.00 + 0.00
Pergamon Press Ltd.

Temperature measurements in a turbulent round plume

NIKOLAS E. KOTSOVINOS
School of Civil Engineering, Democritos University of Thrace, Xanthi, Greece

(*Received* 3 *February* 1984 *and in final form* 7 *August* 1984)

Abstract—The basic objective of this paper is to present and analyze some experimental information regarding the structure of the mean and fluctuating temperature field in a turbulent, vertical round water plume issuing into non-stratified, non-moving ambient water. The focus of this study is the transition of plume-like flows to fully developed self-preserved plumes. One interesting result of this paper is that self preservation of the turbulent field is accomplished at approximately twice the normalized axial distance required for self-preservation of the mean temperature field. It is found that the normalized centerline intensity of temperature fluctuations has an asymptotic value of 44% in the fully developed region.

1. INTRODUCTION

THE STUDY of jets and plumes is important to a wide range of environmental problems, from the disposal of sewage into the ocean through multiport diffusers, to the emission of gas in the atmosphere through stacks.

Most previous investigators have focussed their attention on the structure of the mean and turbulent flow in jet-like flows discharging into a stagnant fluid of same density and therefore experimental data regarding the mean and turbulent flow field in a round plume (i.e. in flows driven primarily by buoyancy forces) are useful.

The turbulent buoyant plume has been a subject of theoretical investigations for more than forty years, (e.g. Batchelor [1], Rouse *et al.* [2]). Experimental investigations have been performed by Rouse *et al.* [2], who used vane anemometers and thermocouples to measure mean velocity and temperature profiles. George *et al.* [3], and Nakagome and Hirata [4] presented mean and turbulent velocity and temperature measurements in a heated round air plume. Ogino *et al.* [5, 6, 7], have measured mean and fluctuations of the vertical velocity and temperature in water plume.

This paper will report on an experimental investigation of mean and turbulent temperature field in a vertical round water plume-like flow, in transition to a fully developed plume. The ambient water is of uniform density and motionless.

2. SCALING PARAMETERS

Given any significant distance to develop, any round buoyant jet which may start as jet-like (high initial momentum flux and small buoyancy flux) will eventually grow like a plume because the initial momentum flux will be a small fraction of the momentum which will be gained by the buoyancy forces.

Definition of the scaling parameters which control whether a buoyant jet is jet-like or plume-like is found in Fischer *et al.* [8] and List [9, 10] where an updated list of references is given. The characteristic length scale $m_0^{3/4}/\beta_0^{1/2}$ (where m_0 and β_0 are the kinematic momentum and buoyancy fluxes at the orifice) is a measure of the distance from the buoyant jet orifice along which the initial momentum flux is important relative to the momentum flux which will be gained by the buoyancy forces. The basic controlling parameter for whether a round buoyant jet is jet-like or plume-like at a distance x from exit is the ratio $x\beta_0^{1/2}/m_0^{3/4}$. For $x \gg m_0^{3/4}/\beta_0^{1/2}$ the flow is plume-like and for $x \ll m_0^{3/4}/\beta_0^{1/2}$ is jet-like.

The initial Richardson number R_0 determines if the flow is plume-like at the origin and is defined as

$$R_0 = \frac{Q_0^2\beta_0}{m_0^{5/2}} = (\pi/4)^{1/2}\frac{(\Delta\rho/\rho_\alpha)gD}{U_0^2} = \frac{0.886}{F_d^2} \tag{1}$$

where Q_0 is the volume flux at exit, ρ_α the ambient density and F_d the densimetric Froude number. The local Richardson number $R(x)$ is defined as $Q^2\beta/m^{5/2}$ where Q, β, m are the local fluxes of kinematic mass, buoyancy and momentum. List and Imberger [11] have shown that in a fully developed plume the local Richardson number is a plume invariant, which for a round plume is approximately equal to $R_p = 0.3$.

Given enough distance to develop, and independently of how small (for jet-like buoyant jets) or how big (for plumes above heating elements) the initial Richardson number might be, the local Richardson number becomes equal to the plume invariant Richardson number $R_p \approx 0.3$, at distance $x\beta_0^{1/2}/m_0^{3/4} \gg 1$.

Subsequently, the scaling of the mean centerline temperature is analyzed. It can be shown (Batchelor [1], Rouse *et al.* [2]) that in a round plume the non-dimensional parameter

$$S = \frac{(\bar{\rho}_M/\rho_\alpha)gx^{5/3}}{\beta^{2/3}} \tag{2}$$

(where $\Delta\bar{\rho}_M$ the centerline density deficiency) should be

NOMENCLATURE

$b, b(x)$	temperature profile halfwidth
C_0	tracer concentration at plume orifice
$\bar{C}_M(x)$	mean centerline tracer concentration
c_p	specific heat
D	diameter of plume orifice
F_d	densimetric Froude number at plume orifice, $U_0/\sqrt{\alpha_0 T_0 g D}$
g	gravitational constant
H	heat flux, $(\pi D^2/4)\rho c_p U_0 T_0$
m_0	kinematic momentum flux at plume orifice
$\overline{q'^2}$	turbulent kinetic energy per unit mass
Q_0	kinematic mass flux at plume orifice
r	radial distance
R_0	Richardson number at $x = 0$ (plume orifice), $Q_0^2\beta_0/m_0^{5/2}$
$R(x)$	local Richardson number
R_f	flux Richardson number
R_p	plume constant, approx. equal to 0.30
S	dimensionless centerline temperature
$\bar{T}_M$	centerline mean excess temperature
$\overline{T'^2_M}$	centerline turbulence intensity
T_0	excess temperature at plume orifice
u, v	velocity in the x and y directions respectively
U_0	velocity at plume orifice
x, y	coordinates.

Greek symbols

α	thermal expansion coefficient
$\beta, \beta(x)$	local kinematic buoyancy flux
β_0	kinematic buoyancy flux at plume orifice
$\Delta\rho_0$	density deficiency at $x = 0$ (plume orifice), $\rho_\alpha - \rho_0$
ε	kinetic energy dissipation rate
η	Kolmogorof length microscale
η_φ	Kolmogorof temperature microscale
ν	kinematic viscosity
ξ	dimensionless distance, $x\beta_0^{1/2}/m_0^{3/4}$
ρ_α	ambient density
ρ_0	density at plume orifice
$\Delta\bar{\rho}_M(x)$	centerline density deficiency.

Subscripts and superscripts

α	ambient
M	plume centerline
0	plume orifice
$'$	fluctuating
$\bar{}$	mean in time.

a constant. In our case $\Delta\bar{\rho}_M/\rho_\alpha = \alpha(x)\bar{T}_M$ where $\alpha(x)$ is the thermal expansion coefficient (which is a function of the absolute temperature of water and therefore, indirectly of distance x) and $\bar{T}(x)$ the mean centerline excess temperature. The buoyancy flux β is related to the conserved heat flux H by the relation

$$\beta(x) = \frac{\alpha(x) g H}{\rho c_p}$$

where $\alpha(x)$ is the local mean value of α determined at the local centerline temperature and therefore, the buoyancy flux is not conserved in thermal water plumes.

The normalized mean centerline temperature, given by equation (2) can be written in the equivalent form

$$S = \frac{\alpha(x)\bar{T}_M(x) g x^{5/3}}{\beta^{2/3}} = (\pi/4)^{-2/3}[\alpha(x)/\alpha(0)]^{1/3} \times \left(\frac{\bar{T}_M}{T_0}\right)(x/D)^{5/3}F_d^{-2/3} \quad (3)$$

where $F_d = U_0(\alpha_0 T_0 g D)^{-1/2}$ is the initial densimetric Froude number.

The controlling parameter $x\beta_0^{1/2}/m_0^{3/4}$ can take the equivalent forms

$$\xi = x\beta_0^{1/2}/m_0^{3/4} = (\pi/4)^{-1/4}(x/D)F_d^{-1} = (\pi/4)^{-1/2}(x/D)R_0^{1/2}. \quad (4)$$

2. EXPERIMENTAL

The round vertical buoyant jet was generated by hot water emerging from a chamber through a nozzle with throat diameter $D = 2.54$ cm. The buoyant jet flow was discharged into a tank, 4×4 m $\times$ 1 m deep, filled with tap water.

Forty centerline measurements were taken for various values of the velocity and temperature at the plume orifice. The temperature of the discharge (which was measured precisely for each run) varied between 41 and 45.80°C. The flow rate of the discharge was measured by a calibrated flowmeter. The exit velocity varied from 7.56 cm s^{-1} to 22.8 cm s^{-1}. The scaling parameter ξ varied between 0.78 and 12.70, and the initial densimetric Froude number F_d from 1.4 to 4.7. The temperature of ambient fluid was kept uniform between 20 and 23°C for all experiments. In order to avoid stratification and free surface effects, measurements were taken between 40 and 80 cm below the free surface. The temperature of the tank water was monitored and found to be reasonably constant for each particular experiment.

The plume temperature was measured using calibrated fast response thermistors of bead diameter 0.3 mm. The bead thermistor was insulated and mounted on a stainless-steel tube, thereby forming a temperature probe. The thermistor temperature response was measured with a bridge circuit, the analog output of which was fed into an analog-to-digital data acquisition system. The data acquisition system digitized the information and packed it on a magnetic tape for data processing with a digital computer. The self heating of the thermistor due to ohmic dissipation was negligible (less than 0.008°C). The thermistor time constant was determined by quickly moving the thermistor from air into a hot water tank (simulation of a step function) and recording at a sampling frequency of 400 Hz the thermistor's response. The time required to obtain 63% of the final reading was found to be 25 ms. The thermistor transfer function was found flat up to 5 Hz. The drift of the thermistor circuit for an extended period of time (3 h), was of the order of 1 mV resulting in an absolute accuracy of the temperature measurements of the order of 0.01°C. Careful consideration was given in the alignment of equipment and complete transverses in many directions were made to check the symmetry of the flow.

A preliminary investigation determined that a sampling time of 150 s was adequate. Large sample time at one measuring point is needed because a turbulent plume includes low frequency components. In order to check roughly the adequacy of spatial and temporal resolution of our thermistor probe for plume-like flow measurements, we estimated that the average kinetic energy dissipation rate was $\varepsilon \sim 0.5\ \mathrm{cm^2\ s^{-3}}$. The Kolmogorof length and temperature microscale are respectively

$$\eta = (\nu^3/\varepsilon)^{1/4} \approx 0.4\,\mathrm{mm}$$

and

$$\eta_\varphi = \eta P_r^{-1/2} \approx 0.14\ \mathrm{mm}.$$

Therefore, the spatial resolution appears to be adequate. Typical Kolmogorof frequency for a typical local mean velocity $U \approx 10\,\mathrm{cm\ s^{-1}}$ is $U/2\pi\eta \approx 40$ Hz. Considering that most turbulent energy is concentrated at low frequencies, the above estimation indicates that the frequency response is also adequate.

3. EXPERIMENTAL RESULTS

Measurements along the axis of the flow were performed for a range of initial Richardson numbers R_0 and normalized axial distances (x/D). A few temperature cross sections were also taken. Subsequently the experimental results are presented and discussed.

Mean temperature field

First of all six mean temperature profiles at the same horizontal plane at $x/D = 12.48$ and at different angular positions were taken in order to check the axisymmetry of the plume flow, and verify the absence of ambient currents which might deform the slowly ascending plumes. The results are plotted in Fig. 1, where a Gaussian curve has been fitted of the form

$$\bar{T}(x,r) = \bar{T}_M \exp\{-(\ln 2)[r/b(x)]^2\}$$
$$= \bar{T}_M \exp(-69r^2/x^2).$$

It is now well established that when proper experimental precautions are taken (e.g. avoiding ambient currents, using a large tank to avoid stratification, using a large sampling time) then the experimental results of mean temperature or concentration field, in plumes or jets, round or plane, are fitted excellently by Gaussian curves.

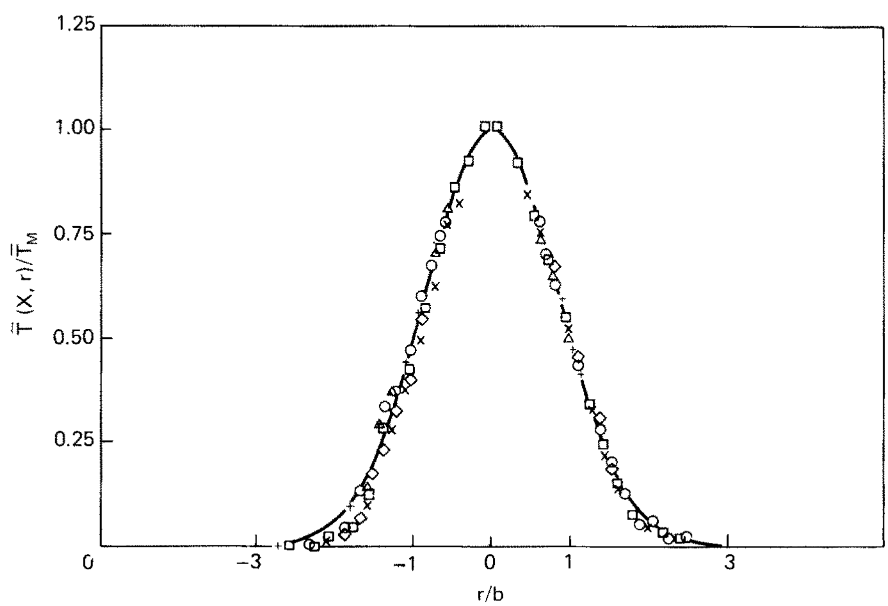

FIG. 1. Six mean temperature profiles at the same distance from plume orifice but at different angular positions to check the axisymmetry; $x/D = 12.48$; $x\beta_0^{1/2}/m_0^{3/4} = 4.7$; $b/D = 1.33$. The Gaussian curve is given by $\bar{T}(x,r) = \bar{T}_M(x)\exp(-69r^2/x^2)$.

The temperature halfwidths, determined from the measured mean temperature cross sections, normalized using the distance from the exit ($x = 0$) without any correction for virtual origin, are plotted in Fig. 2 against the controlling parameter $x\beta_0^{1/2}/m_0^{3/4}$, which is a measure of the local importance of the buoyancy forces relative to input inertia forces. In the same Fig. 2 are plotted the experimental data of George *et al.* [3] and Nakagome *et al.* [4] for round air plume-like flows, of Birch *et al.* [12] for a round methane jet into air ($\rho_{methane}/\rho_{air} \approx 0.56$), and of Becker *et al.* [13] for a round air jet without buoyancy ($x\beta^{1/2}/m_0^{3/4} = 0$).

The following relation for the halfwidth $b(x)$ is obtained from Fig. 2

$$b(x) \approx 0.1x.$$

This result should be compared with the result for pure jets ($\beta = 0$) which are tabulated by Fisher *et al.* [8, Table 9.1] where it is suggested, independently of the molecular Schmidt number, that $b \approx 0.106x$. Chen and Rodi [14] suggest in their review that $b \approx 0.1\,x$. Birch *et al.* [12] measured concentration in a round free methane jet in air and they found that $b(x) \approx 0.097x$. Therefore, the basic assumption of the List and Imberger theory [11] is further confirmed, i.e. to the first approximation the rate of growth (angle of expansion) of any round buoyant jet in its transition from a jet-like flow to a plume is independent of the value of the parameter $x\beta^{1/2}/m_0^{3/4}$ (i.e. independent of the initial Richardson number and of the normalized distance x/D, and independent of the local importance of buoyancy forces). Moreover, it is independent of density ratio, at least for $\rho_{jet}/\rho_{ambient} < 0.5$ (Birch *et al.* [12]).

The centerline mean temperature normalized using equation (3), is plotted in Fig. 3 vs the controlling parameter $\xi = x\beta_0^{1/2}/m_0^{3/4}$. The data are fitted by the semi-empirical curve

$$S = \frac{\alpha(x)\bar{T}_M g x^{5/3}}{\beta(x)^{2/3}} = 5.304\xi^{2/3}(2+0.219\xi^2)^{-1/3} \quad (5)$$

or

$$\frac{\bar{T}_M(x)}{T_0} = 4.94\left[\frac{\alpha(0)}{\alpha(x)}\right]^{1/3} \times (x/D)^{-1}[2+0.246(x/D)^2F_d^{-2}]^{-1/3}.$$

We observe in Fig. 3 that the normalized mean centerline temperature S becomes asymptotic to a constant, reaching self-preservation for $\xi > 7$, i.e. for $\xi > 7$ we have $S = 8.8$ or

$$\left[\frac{\alpha(x)}{\alpha(0)}\right]^{1/3}\frac{\bar{T}_M}{T_0}(x/D)^{5/3}F_d^{-2/3} = 7.88.$$

The experimental results of Ogino *et al.* [5] for the decay of centerline temperature in uniform temperature ambient are plotted in Fig. 3, and apparently they are in good agreement with our results.

Turbulence

The centerline turbulence intensity $\overline{T_M'^2}$, normalized by local mean temperature $\bar{T}_M(x)$ along the jet axis, is plotted in Fig. 3 vs the non-dimensional parameter $x\beta_0^{1/2}/m_0^{3/4}$. It can be observed that the normalized turbulence intensity increases with an increase in the parameter $x\beta_0^{1/2}/m_0^{3/4}$ and for $x\beta_0^{1/2}/m^{3/4} > 14$ becomes a constant approximately equal to 0.44, which is 70% higher than the centerline turbulent temperature intensity 0.255 found by Antonia *et al.* [15] in a heated jet with a co-flowing stream. Therefore the normalized centerline intensity of turbulent temperature fluctuations in the fully developed plume is much higher than the intensity of turbulent temperature fluctuations found in jets or jet-like flows, e.g. Becker *et al.* [13], Laurence [16], Birch *et al.* [12].

The normalized radial profile $\sqrt{\overline{T'^2}}(x,r)/\sqrt{\overline{T_M'^2}}(x)$ of intensity of temperature turbulent fluctuations in a round plume is plotted in Fig. 4 against the non-dimensional radial distance r/b. In the same figure the experimental data of George *et al.* [3], Nakagome and

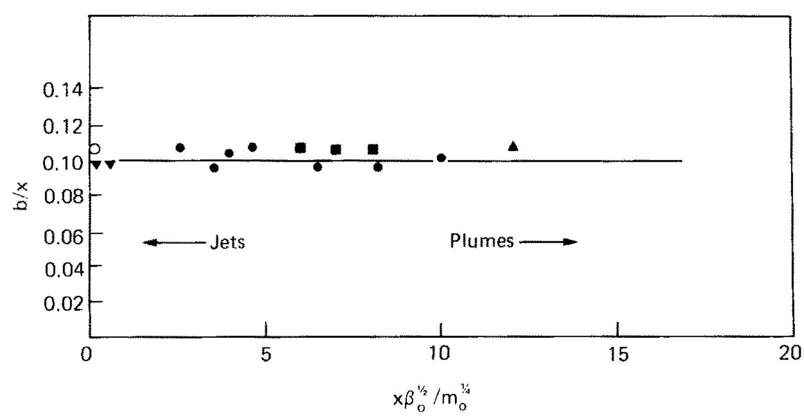

FIG. 2. Dimensionless temperature halfwidth b/x, as a function of dimensionless distance $x\beta_0^{1/2}/m_0^{3/4}$. ●, present author; ○, Becker *et al.* [13]; ▲, George *et al.* [3]; ■, Nakagome and Hirata [4]; ▼, Birch *et al.* [12].

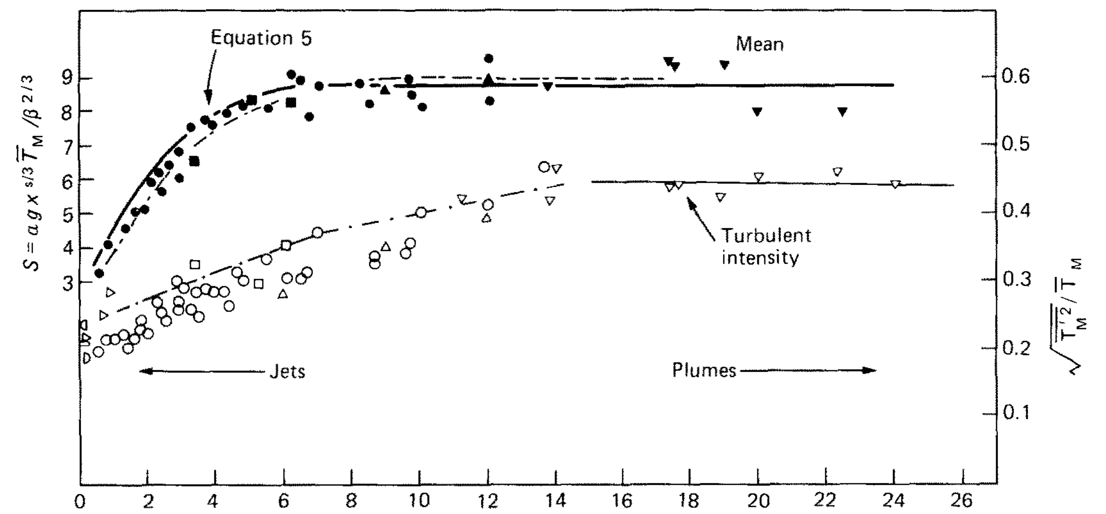

FIG. 3. Round plume: normalized centerline mean temperature equation 5 and temperature turbulence intensity $\sqrt{\overline{T_M'^2}}/\bar{T}_M$ as a function of dimensionless distance $x\beta_0^{1/2}/m_0^{3/4}$. Solid symbols are for mean temperature and open for turbulence intensity; ○, present work; ◐, Antonia *et al.* [15]; ▷, Birch *et al.* [12]; ⌓, Becker *et al.* [13]; △, George *et al.* [3]; ▽, Kotsovinos and Pantokratoras [17]; □, Nakagome and Hirata [4]; D, Wilson and Danckwerts [18]; ·—·—·—, Ogino *et al.* [6].

Hirata [4], and Ogino *et al.* [6] are plotted. It is interesting to notice that the lateral distribution of the turbulence intensity is almost flat for $r/b < 1$ for larger values of ξ.

The impact of buoyancy upon the turbulence in a round plume is now discussed.

The importance of the buoyant production of turbulent energy relative to shear-stress production is found using the turbulent energy equation, which can be integrated across the plume to eliminate the dependence on r

$$\int_{\text{plume}}^{2\pi} \frac{d\overline{q'^2}}{dt} r\,dr = -\left[\int_{\text{plume}}^{2\pi} \overline{u'v'} \times \frac{\partial \bar{u}}{\partial r} r\,dr\right](1+\bar{R}_f) + \text{other terms}$$

where the gross importance of the buoyant production over the shear production is given by the 'integrated' flux Richardson number

$$\bar{R}_f = \int_{\text{plume}}^{2\pi} g\overline{\rho' u'} r\,dr \left[\int_{\text{plume}}^{2\pi} \overline{u'v'} \frac{\partial \bar{u}}{\partial r} r\,dr\right]^{-1}.$$

An order of magnitude analysis indicates that

$$\bar{R}_f = O(\Delta\rho g\, b/\rho_a U^2) = O(R(x))$$

where U, $\Delta\rho$ and b are respectively the characteristic local velocity, density and length scales across the buoyant jet, and $R(x)$ is the local jet Richardson number. In a fully developed plume, $R(x)$ is constant, approximately equal to $R_p = 0.3$, and in a pure jet $R(x) = 0$ (see List and Imberger [11], Fisher *et al.* [8]). Therefore it seems reasonable to argue that the gross (across the plume) production of turbulent energy by buoyancy forces is a substantial part of the gross turbulent shear production.

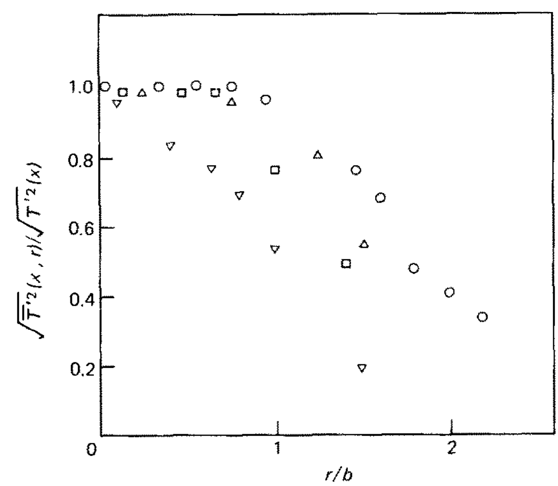

FIG. 4. Normalized radial profile of intensity of temperature turbulent fluctuations in round plumes against dimensionless radial distance r/b. ○, this work, $\xi = 12, 70$; △ George *et al.* [3], $\xi = 12, 11$; ▽ Nakagome and Hirata [4], $\xi = 6$; □ Ogino *et al.* [6], $\xi > 6, 6$.

Transition to fully developed, self preserved plume

It is clear from Fig. 3 that the normalized centerline mean temperature S becomes constant for $\xi = x\beta_0^{1/2}/m_0^{3/4} > 7$ and that the normalized centreline turbulence intensity $(\overline{T_M'^2})^{1/2}/\bar{T}_M$ becomes constant for $\xi > 14$. Apparently turbulence reaches self-preservation at a normalized distance which is approximately twice the distance needed for the mean temperature field to reach self-preservation. Therefore round plume-like flows become fully developed, self-preserved round plumes for $x\beta_0^{1/2}/m_0^{3/4} > 14$. George *et al.*'s [3] experiments with an initial densimetric Froude number of 1.4 (or $R_0 = 0.48$) and $x/D = 8$, 12 and 16, correspond to $\xi = 1.06\ (x/D)F_d^{-1} = 6.06$, 9.09 and 12.11. respectively, and evidently were in a region where turbulence intensity is still in transition towards the asymptotic plume value. It should be noted that George *et al.*'s experiments were done with an initial Richardson number $R_0 \approx 0.48$, which is larger than the plume Richardson number R_p, which is estimated by List and Imberger [11] to be 0.3. This is interesting because it indicates that even plumes issued with initial Richardson number larger or equal to plume Richardson number $R_p \approx 0.3$ ('pure plumes') do not automatically reach self-preservation but require a distance x/D calculated from the equation (4) using $R_0 = R_p$, i.e. from

$$x\beta^{1/2}/m^{3/4} = 1.12\sqrt{R_p}(x/D) = 14$$

which for $R_p \approx 0.30$ gives $x/D \approx 22.8$.

These arguments are in agreement with the experimental results of Nakagome and Hirata [4], which are also plotted in Fig. 3, these experiments were performed above a round heater and therefore the parameter $x\beta_0^{1/2}/m_0^{3/4}$ is estimated from the equivalent equation (4), where D is the diameter of the heated element and $R_0 \approx R_p \approx 0.3$, i.e.

$$\xi = 1.12\sqrt{R_p}(x/D) \approx 0.61(x/D).$$

The largest value of x/D used by Nakagome and Hirata was 11.5 which gives $\xi = x\beta_0^{1/2}/m_0^{3/4} \approx 7$, indicating that turbulence is still in a transition process and that their flow is not a fully developed plume.

4. CONCLUDING REMARKS

One interesting suggestion of this study is that plumes generated above heated elements (usually called 'pure plumes'), need enough distance to achieve self preservation. It is estimated that the turbulent temperature field in a pure round plume generated above a heated disk of diameter D reaches self preservation at $x/D \approx 24$.

Any round buoyant jet becomes a fully developed, self-preserved plume at a distance $x\beta_0^{1/2}/m_0^{3/4} > 14$ or at $(x/D)R_0^{1/2} > 12.5$.

The angle of expansion of the mean temperature field is, to the first approximation, independent of the axial distance x/D and of the initial Richardson number (i.e. independent of the nature of the driving force).

The normalized, centerline intensity of turbulent temperature fluctuations in a fully developed round plume is

$$\sqrt{\overline{T_M'^2}}/\bar{T}_M \approx 0.44.$$

Acknowledgement—The experimental work and the analysis of the experimental data was carried out while the author was a Research Fellow in the W. M. Keck Laboratory of Hydraulics Water Resources of the California Institute of Technology during the 1975–76 academic year. The author is grateful to Professor E. J. List for numerous constructive and enlightening discussions. The financial support of U.S. National Science Foundation (Grant No. ENV. 75-02985), of NATO (Research Grant 117.80/81) and of Greek Ministry of Education is gratefully acknowledged. I gratefully also acknowledge the valuable comments of the reviewers of this paper.

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MESURES DE TEMPERATURE DANS UN PANACHE TURBULENT CIRCULAIRE

Résumé—On présente et on analyse des expériences sur la structure des champs de température moyenne et fluctuante dans un panache turbulent, vertical, circulaire pénétrant dans l'eau non stratifiée mais sans mouvement d'ensemble. Le centre de cette étude est la transition vers les sillages pleinement développés. Un résultat intéressant est que l'autopréservation du champ turbulent est accomplie à approximativement deux fois la distance axiale normalisée nécessaire pour l'autopréservation du champ de température moyen. On trouve que l'intensité normalisée des fluctuations de température a une valeur asymptotique de 44% dans la région pleinement établie.

TEMPERATURMESSUNGEN IN EINEM TURBULENTEN RUNDEN AUFTRIEBS-STRAHL

Zusammenfassung—In dieser Abhandlung werden experimentelle Daten über die Struktur des Temperaturfeldes (Mittelwerte und Schwankungen) in einem turbulenten vertikalen runden Wasserstrahl, der in nichtgeschichtetes, unbewegliches Wasser einströmt, vorgestellt und untersucht. Der Schwerpunkt dieser Studie ist der Übergang von einer strahlähnlichen Strömung zu einem voll ausgebildeten, stabilen Strahl. Ein wichtiges Ergebnis dieser Untersuchung ist, daß die selbständige Aufrechterhaltung der turbulenten Strömung in nahezu der doppelten axialen Entfernung erzielt wird wie die selbständige Aufrechterhaltung des mittleren Termperaturfeldes. Es wurde herausgefunden, daß die Intensität der normierten Temperaturschwankungen in der Mittellinie einen asymptotischen Wert von 44% derjenigen im Gebiet der voll ausgebildeten Strömung hat.

ИЗМЕРЕНИЯ ТЕМПЕРАТУРЫ В КРУГЛОЙ ТУРБУЛЕНТНОЙ СВОБОДНОКОНВЕКТИВНОЙ СТРУЕ

Аннотация—Основной целью работы является представление и анализ экспериментальных данных по структуре среднего и пульсационного температурного поля в турбулентной вертикальной свободноконвективной струе воды, истекающей в нестратифицированную, неподвижную окружающую воду. В центре исследования—переход к автомодельному режиму. Интересно, что автомодельность турбулентного поля достигается на расстоянии приблизительно равном двум нормализованным осевым расстояниям, необходимым для автомодельности среднего температурного поля. Найдено, что нормализованная интенсивность температурных пульсаций на оси струи в полностью развитой зоне имеет асимптотическое значение, равное 44%.