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Ice Control with Thermal/Bubbler Plumes : *Line Source Configuration*

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ABSTRACT

A thermal/bubbler plume theory is presented . The formulation applies to any thermal/bubbler combination including the thermal and the bubbler limiting cases. A computer model is used to study the properties of thermal/bubbler plumes and examine their interaction with an ice cover. The computer model provides a tool to design and optimize the operation of thermal/ bubbler installations.

For typical conditions prevailing under an ice cover, the study shows that a minimum supply of air would have to be released in order to convey the thermal flux to a specified height. The calculations also reveal the existence of a critical supply of air above which a given thermal flux may be conveyed to any elevation above the source.

This paper is devoted to the line source configuration of a thermal/bubbler plume. The point source configuration will be addressed separately in Baddour (1988)

INTRODUCTION

Considerable amount of research on buoyant jets and plumes has been conducted during the last few decades. These flows are technologically and environmentally important and constitute a major subject area in the field of turbulence. A state-of-the-art review on jets and plumes may be found in List(1982).

The intense research activity in the field of jets and plumes has contributed in the development of analytical and numerical methods to predict the behaviour of these flows. For simple flow configurations the so-called " integral models " are practical and sufficiently accurate in their description of the flow behaviour.

Most previous studies on jets and plumes are not, however, generally applicable to thermal plumes in a water environment. It is certainly the case for winter conditions. This is due to the peculiar non-linear relationship between the density and temperature of water, and the fact that the water density reaches its maximum at about $4^{o}C$. The equation of state of water for temperature varying between $0^{o}C$ and $15^{o}C$ is presented in Fig. 1. This function may be accurately fitted with a third order polynomial.

The density-temperature relationship defined above generates buoyancy forces that would drive thermal plumes upwards in a range of temperature and downwards in another range of temperature. This *reversible buoyancy* causes thermal plumes to sink when they mix with ambient water at temperature near the freezing mark. Because of this phenomenon, thermal plumes, by themselves, would have limited ice control capabilities.

A bubbler plume, on the other hand, produces a surface current made of ambient water entrained from lower depths. During the winter, when the water at lower depths is slightly warmer than the freezing temperature, the surface current generated by the bubbler has proven in many cases to be useful in suppressing ice in navigation channels, within and around locks and in small harbors.

The analysis of bubbler plumes may be traced back to G.I. Taylor (1955) who worked on the idea of bubble breakwater. Further analyses of bubbler plumes were later made by Kobus (1968), Cederwall and Ditmars (1970), and Abraham et al (1973). More recently, Ashton [(1978),(1979)] examined the interaction of bubbler plumes with an ice cover and applied the results obtained by Kobus to simulate the performance of bubbler systems.

The control of ice with bubbler plumes is sometimes inadequate. Examples are bubbles used in shallow enclosures and well mixed water bodies. Under these conditions the water temperature would be very close to the freezing mark throughout the depth after short periods of bubbler operation.

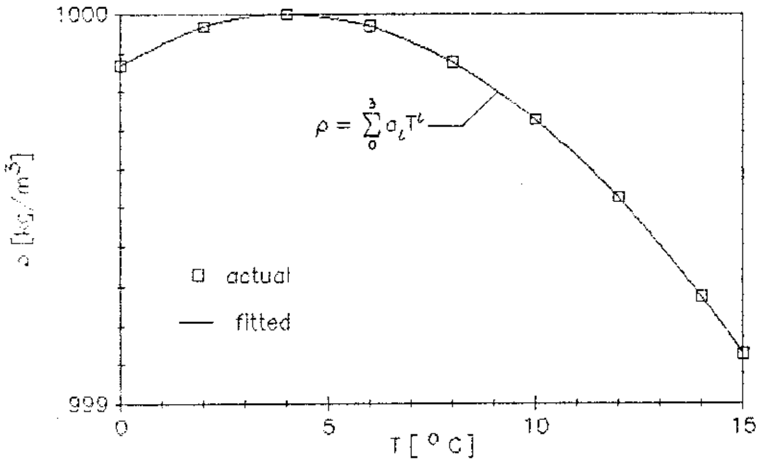

Fig.1 Non-linear equation of state

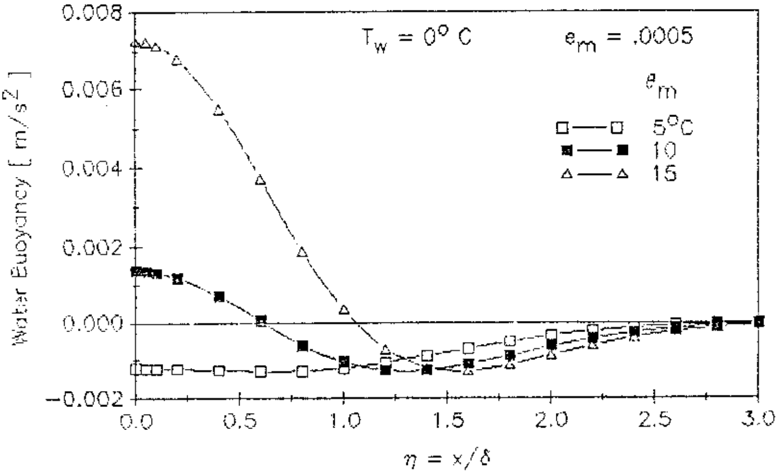

Fig.2 Water buoyancy profiles

This study is concerned with the behaviour plumes generated by a simultaneous release of warm water and air. They are referred to as *thermal/bubbler plumes* . The research is focusing on the ice control capability of thermal/bubbler systems. In such systems the warm water released, and the ambient water entrained into the plume, would provide a reliable source of heat for ice control. The air injected would provide the positive buoyancy needed to counteract the negative buoyancy of the warm water.

Presently no information seems to be available on this kind of plumes. This study was, therefore, conducted to fill this gap and to improve the basic understanding thermal/bubbler behaviour. Advancement in this field would allow the development of effective designs of thermal/bubbler systems. The various class of plumes considered are schematically shown in Fig. 3.

THERMAL/BUBBLER PLUME THEORY

A thermal/bubbler plume is essentially a *two-phase flow* in which the water phase is (i) turbulent, (ii) non-homogeneous and (iii) governed by a non-linear equation of state. To avoid further complexities the heat transfer between air and water phases of the plume is assumed negligible.

Consider the two-dimensional thermal/bubbler plume shown in Fig.1-c. The integral variables characterizing the development of the plume are :

[1] q = air flow $= \int e(U+u_b)\,dx$

[2] Q = water flow $= \int (1-e)U\,dx$

[3] M = momentum flux $= \int (1-e)U^2 dx$

[4] ϕ = Thermal flux $= \int (1-e)U\,\theta\,dx$

where

e = concentration of air by volume
U = mean water velocity in the z-direction
u_b = single bubble rise velocity in stagnant water
$\cong$ 0.30 m/s for a wide range of bubbles.
θ = $T-T_w$ = excess water temperature
T_w = $T_w(z)$ = ambient water temperature
x = horizontal coordinate
z = vertical coordinate pointing up.

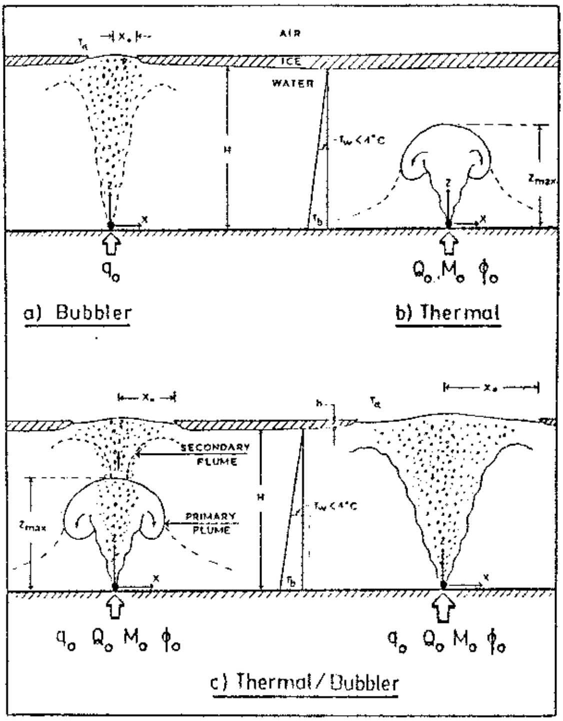

Fig.3 Various class of plumes

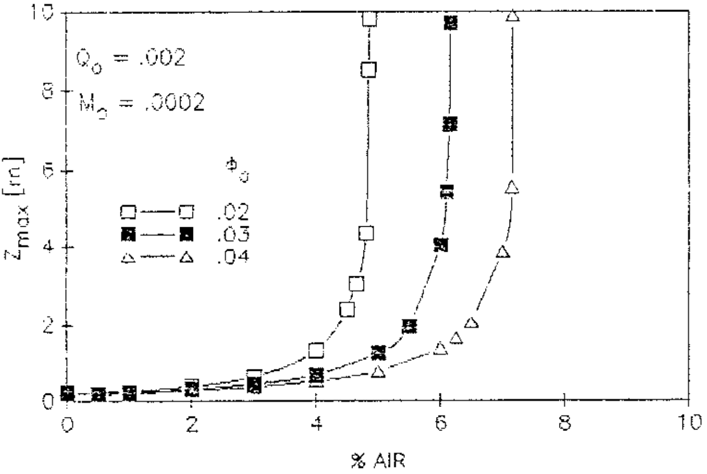

Fig.4 Effect of thermal flux on z_{max}

In this type of flow, the mean velocity, the mean excess temperature and the mean air concentration profiles would be well represented by gaussian functions, i.e.

[5] $$U = U_m \exp\,[-(x/\delta)^2\,]$$

[6] $$\theta = \theta_m \exp\,[-(x/\delta_\theta)^2]$$

[7] $$e = e_m \exp\,[-(x/\delta_e)^2]$$

where δ, δ_θ and δ_e are, respectively, the velocity width , the temperature width and the air concentration width of the plume. Subscript "m" refers to the maximum values occuring along the plume center-line. In the fully developped region of the flow δ_θ and δ_e are proportional to δ , i.e.

[8] $$\lambda_\theta = \delta_\theta / \delta \qquad \& \qquad \lambda_e = \delta_e / \delta$$

may be treated as constant parameters. From results of previous plume studies, it seems reasonable to set $\lambda_\theta = 1.35$ and $\lambda_e = 0.20$ for a thermal/bubbler plume . Note, however, that the bubble size distribution may have some effect on the magnitude of λ_e , but presently we know very little about it.

Implementing the profiles defined in Eqs 5, 6 and 7, the integral variables given in Eqs 1 to 4 become :

[9] $$q = I_{eu}\, e_m\, U_m\, \delta + I_e\, e_m\, u_b\, \delta$$

[10] $$Q = I_u\, U_m\, \delta - I_{eu}\, e_m\, U_m\, \delta$$

[11] $$M = I_{uu}\, U_m^2\, \delta - I_{euu}\, e_m\, U_m^2\, \delta$$

[12] $$\phi = I_{u\theta}\, U_m\, \theta_m\, \delta - I_{eu\theta}\, e_m\, U_m\, \theta_m\, \delta$$

where I_u , I_{uu} , $I_{u\theta}$, I_e , I_{eu} , I_{euu} and $I_{eu\theta}$ are profile shape parameters given by :

[13] $$I_u = \sqrt{\pi}$$

[14] $$I_{uu} = \sqrt{\pi/2}$$

[15] $$I_e = \lambda_e \sqrt{\pi}$$

[16] $$I_{u\theta} = \lambda_\theta \left(\frac{\pi}{1 + \lambda_\theta^2} \right)^{0.5}$$

[17] $$I_{eu} = \lambda_e \left(\frac{\pi}{1 + \lambda_e^2} \right)^{0.5}$$

[18] $$I_{euu} = \lambda_e \left(\frac{\pi}{1 + 2\lambda_e^2} \right)^{0.5}$$

[19] $$I_{eu\theta} = \lambda_e \lambda_\theta \left(\frac{\pi}{\lambda_e^2 + \lambda_e^2 \lambda_\theta^2 + \lambda_\theta^2} \right)^{0.5}$$

The buoyancy force per unit mass of water is $g'=g(\rho_w - \rho)/\rho_w$, where ρ is the density and ρ_w is the ambient density at the same level. The equation of state shown in Fig.1 governs the relation between the density ρ and temperature T. This relation is well approximated by

$$\rho = \sum a_\ell T^\ell \quad , \quad \ell = 0,3 \tag{20}$$

with $a_0 = 999.8676 \ \mathrm{kg.m^{-3}}$
$a_1 = 0.06742 \ \mathrm{kg.m^{-3}.^{o}C^{-1}}$
$a_2 = -0.008875 \ \mathrm{kg.m^{-3}.^{o}C^{-2}}$
$a_3 = 0.000073 \ \mathrm{kg.m^{-3}.^{o}C^{-3}}$

Accordingly, the buoyancy force per unit mass of water is :

$$g' = -\frac{g}{\rho_w} \sum b_\ell \theta^\ell \quad , \quad \ell = 1,3 \tag{21}$$

where b_ℓ are functions of a_j; $j = 1,3$ and T_w .

Typical profiles of buoyancy determined using Eq. 21 are presented in Fig.2. It is interesting to see how the negative buoyancy gradually dominates the entire plume as the centerline temperature decreases.

Finally the total buoyancy of the air/water mixture is calculated as

$$G = G_w + G_a \tag{22}$$

where "w" and "a" refer to water and air. The water component of the buoyancy force is

$$\begin{aligned} G_w &= \int (1-e) g' dx \\ &= \frac{-g\delta\sqrt{\pi}}{\rho_w} \sum b_\ell \theta_m^\ell \left(\frac{\lambda_\theta}{\sqrt{\ell}} - c_\ell e_m \right) \ ; \quad \ell = 1,3 \end{aligned} \tag{23}$$

where $c_\ell = c_\ell(\lambda_\theta, \lambda_e)$

and the air component of the buoyancy force is

$$G_a = \int e g dx \tag{24}$$

GOVERNING EQUATIONS

In terms of the quantities defined in the previous section , the governing equations of a thermal/bubbler plume may be summarized as follows:

i- *Continuity of water phase*

A modified entrainment hypothesis adapted to thermal/bubbler plume conditions is :

[25] $$dQ/dz = 2(\alpha\ U_m + \beta u_b)$$

The term " βu_b" represents a wake (or drag) component of turbulent entrainment. This additional component seems to have been overlooked in previous bubbler analyses. The entrainment coefficient α is known to be of the order of 0.1 for two-dimensional plumes [see List(1982)]. Until further research is conducted to determine the magnitude of β , it is temporarily assumed in the computer model that $\alpha = \beta = 0.1$.

ii- *Continuity of air phase*

For isothermal air conditions we have :

[26] $$q = q_o\ p_{atm}\ /\ [\ p_{atm} + \int_z^H \rho_w g\ dz\ ]$$

where q_o is the flow of air released per unit-length of diffuser evaluated under atmospheric pressure p_{atm} . H is the total depth of water above the source of air.

iii) *Momentum equation*

The momentum equation is simply

[27] $$dM/dz = G$$

iv) *Thermal energy equation*

and conservation of thermal energy yields

[28] $$d\phi/dz = -(dT_w/dz)\ Q$$

The above set of four equations can uniquely determine the pertinent plume variables at any distance from the source. The initial conditions to impose at $z = 0$ are $q = q_o$, $Q = Q_o$, $M = M_o$ and $\phi = \phi_o$. To avoid singularities at $z = 0$ a transition zone is incorporated in the computer model. In this transition zone the profiles of U,θ and e are allowed to change from uniform to gaussian.

DISCUSSION

Figs. 5 and 6 show the variation of buoyancy force G and momentum flux M along a thermal/bubbler plume. These two figures are presented to demonstrate the importance of air supply in counteracting the reversible buoyancy. When the air supply is too low , the net buoyancy force reduces continuously. In this case , the bulk of the heat flux would only be conveyed to a limited height z_{max} . And a *secondary plume* carrying a reduced amount of heat is likely to emerge from the lower plume as visualized in Fig. 3c. The effect of heat flux on the maximum attainable height z_{max} is shown in Fig. 4.

The calculations seem also to suggest that if the air supply exceeds a *critical value* the thermal flux may be conveyed to any height above the source. For example in Figs. 4 and 5 the critical air supply is about 7.19% of the water supply Q_o.

CONCLUDING REMARK

The theory presented in this paper is revealing new and interesting features about the behaviour of thermal/bubbler plumes. The computer model developed appears capable of determining the essential properties of the plume and to simulate its thermal interaction with an ice cover.

At this stage of the research both field and laboratory investigations are needed to assess the assumptions and the accuracy of the predictions.

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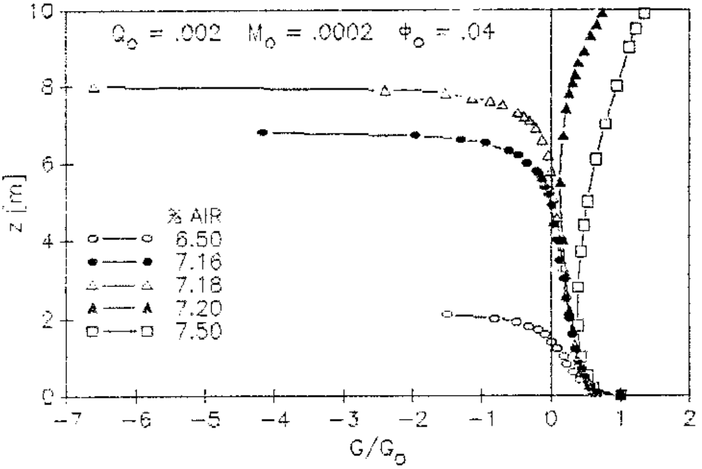

Fig.5 Buoyancy of water/air mixture

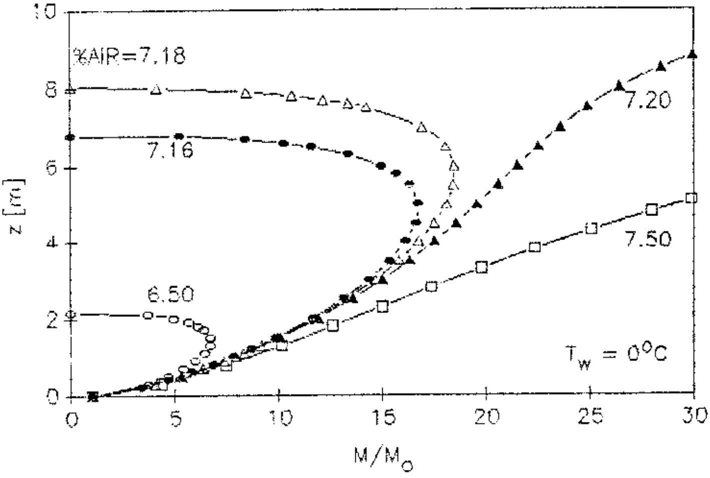

Fig.6 Momentum flux

DISCUSSION

R. Gerard

Have you done an overall energy balance to compare the energy required to generate a water jet (easy to get it down, but lots of energy to generate the jet) against the energy required to generate an air-bubble plume (moves up under buoyancy but has to be compressed to get it to the bottom)?

Reply

I have not explicitly considered such comparison since the thermal/bubbler plume does not rely on the initial momentum of the released water to convey the heat to the surface. Away from the source, the upward plume momentum is essentially air-induced. Without air assistance, the initial momentum required to counteract the reversible buoyancy is too large, and in many cases would be practically unfeasible to provide.

J. Wuebben

A follow-up to a comment made concerning the use of thermal/bubbler plumes for ice jam control.

Waste heat has been recently used to control ice on the Kankakee river in the United States. However, since ice jams occur on flowing water, the vertical mixing is more than sufficient and bubblers should not be necessary.

Reply

I certainly agree that in fast moving turbulent reaches, the released heat can be effectively transported for ice control, without air assistance. Nevertheless, I would think that air assistance in transporting heat might be found useful in more quiescent slow moving reaches.