In the same figure, the value of δ_l obtained by Tachibana *et al.* [1], using stainless steel strips is reported. Finally, the experimental data obtained may be expressed by a simple relation of the form:

$$\delta_l = 2.35\cdot 10^{-4}\left(\frac{\sqrt{(k\rho c)}}{10^4}\right)^{-3.26}, \text{m}.$$

CONCLUSIONS

The experimental results obtained in the present research point out the considerable effect of the thickness of the walls on burnout heat flux. This effect, however, is present for the values of the thickness δ below a definite limiting value δ_l, characteristic of the metal tested.

Restricted to the experimental conditions here examined, the value of δ_l, defined to correspond to the ratio $\varphi_{b.o.}/\varphi^*_{b.o.}$ equal to 0.9, depends on the parameter $\sqrt{(k\rho c)}$ of the heating wall.

REFERENCES

1. F. Tachibana, M. Akiyama and H. Kawamura, Non-hydrodynamic aspects of pool boiling burnout, *J. Nucl. Sci. Technol.* **4**(3), 121–130 (1967).
2. M. Carne and D. H. Charlesworth, Thermal conduction effects on the critical heat flux in pool boiling, *Chem. Engng Prog. Symp. Ser.* **62**, 24–34 (1966).
3. H. J. Ivey and O. J. Morris, The effect of test section parameters on saturation pool boiling burnout at atmospheric pressure, A.I.Ch.E. Preprint 16, Chicago (1962).
4. H. J. Ivey and O. J. Morris, Burnout in subcooled pool boiling at atmospheric pressure, U.K.A.E.A., Rep., A.E.E.W., 157 (1967).
5. W. R. Houchin and J. H. Lienhard, Boiling burnout in low thermal capacity heaters, A.S.M.E. Paper presented at the Winter Annual Meeting and Energy System Exposition, New York, November–December (1966).
6. M. Carne, Some effect of test section geometry in saturated pool boiling on the critical heat flux for some organic liquid mixtures, *Chem. Engng Prog. Symp. Ser.* **61**, 281–289 (1965).
7. E. K. Averin, The effect of the material and of the mechanical treatment of the surface in the heat exchange in the boiling of water, *Izv. Akad. Nauk. SSSR Otdel Tekh. Nauk.* **3**, 166–172 (1954).
8. R. Roemer, The effect of power transients on peak heat flux, *Int. J. Heat Mass Transfer* **12**, 953–964 (1969).
9. U. Magrini, Boiling burnout on thin walls: influence of wall properties, Report No. 11 (FTR-11), Genova (May 1972).
10. G. Guglielmini, U. Magrini and E. Nannei, Flusso termico di "burnout" in "pool boiling" su tubi a pareti sottili, Paper presented at the XXIX Congresso Nazionale A.T.I. (Associazione Termotecnica Italiana), Torino, Italy (September 1974).
11. A. Goldsmith, T. E. Waterman and H. J. Hirschhorn, *Handbook of Thermophysical Properties of Solid Material*, Vol. 1. McMillan, New York (1959).
12. F. E. Fowle, *Smithsonian Physical Tables*, 8th Edn. Smithsonian Institution, Washington, D.C. (1934).

Int. J. Heat Mass Transfer. Vol. 19, pp. 1075–1076. Pergamon Press 1976. Printed in Great Britain

A CONSIDERATION ON NATURAL CONVECTIVE SWAYING MOTION OF PLUME ABOVE A HORIZONTAL HEATED PLATE

S. Aiba
Department of Mechanical Engineering, Akita Technical College, Akita, Japan
and
N. Seki
Department of Mechanical Engineering, Hokkaido University, Sapporo, Japan

(*Received* 5 *January* 1976)

NOMENCLATURE

- d, heater width;
- f, frequency;
- G_{rd}, Grashof number;
- H, distance from the heated surface to the liquid surface;
- Pr, Prandtl number;
- t, temperature;
- ν, kinematic viscosity;
- τ, period.

1. INTRODUCTION

An oscillation of natural convective flow in a horizontal cylindrical annuli was examined by Bishop *et al.* [1, 2], while the swaying motion of plume rising from a horizontal line heat source was investigated by Forstrom and Sparrow [3], Fujii *et al.* [4]. Miyabe *et al.* [5] observed a plume rising from a horizontal heated cylinder by using a spindle oil. However, the physical understanding on the continuation of such swaying motion of plume or its effect on heat transfer has not been fully made so far.

In this note the swaying motion of plumes rising from a horizontal plate is discussed under an assumption that the motion might be a self-excited oscillation related to a periodical variation of local heat transfer on the surface.

A nondimensional relation between the oscillating frequency of plume and Grashof number is also demonstrated.

2. RESULTS AND DISCUSSION

Measuring procedure

Several kinds of stainless steel foil (400 mm in length, 0.03 and 0.05 mm in thickness, 10, 20 and 30 mm in width) are fixed as heaters on an acryle plate (10 × 100 × 400 mm). The horizontality of every heater placed in oil, which is put into a glass vessel test chamber (300 mm wide, 600 mm long and 360 mm high), is carefully checked. Frequencies of the various swaying motions are evaluated from the results measured with Cu–Co thermocouple of 0.065 mm dia, which is located at a distance s of 30–40 mm vertically above the middle of the width of the heater.

Experiments are carried out for Prandtl number ranging from 80 to 160 under the following conditions, $l = 400$ mm, $H = 95$–300 mm, $Q = 10.5$–53.5 W/m (for $d = 10$ mm), 24.9–47.7 W/m (for $d = 20$ mm), 34.9–80.2 W/m (for $d = 30$ mm), where l is a length of heater, H is a distance from the heated surface to the liquid surface, d is a width of heater and Q is a heat supplied per unit length. Grashof number (based on d) ranges from 6.0×10^3 to 2.0×10^6.

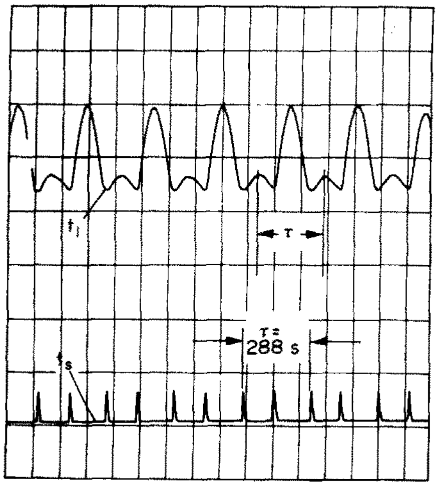

FIG. 1. An example of measured periodical temperature variation for transformer oil.

ment of the plume from the equilibrium. Therefore the equation governing such a motion might be virtually described in the following form:

$$m\ddot{x} + plx = 0 \qquad (1)$$

where m is a mass of plume. Assuming m as $m = c_1 \rho dlH$ with constant c_1 and stiffness constant per unit length p as $p = c_2 bd\psi(Pr)$ with constant c_2, whose relation is to be introduced by a dimensional analysis for p in the neighborhood of the heated surface, dimensionless frequency of plume fd^2/ν could be correlated using equation (1) as follows,

$$fd^2/\nu = cF(Pr)\{G_{rd}d/H\}^{\frac{1}{2}} \qquad (2)$$

where c is a constant, $F(Pr)$ is a function of Prandtl number, f is a frequency of plume, $G_{rd}(=g\beta d^3 Q/\nu^2\lambda)$ is Grashof number, and b, ν, ρ and λ are buoyancy force, kinematic viscosity, density, thermal conductivity, respectively.

Experimental results in Fig. 2 demonstrate that the dimensionless basic frequency correlates well with $G_{rd}d/H$ as is shown in the following relation,

$$fd^2/\nu = 1.37 \times 10^{-3}\{G_{rd}d/H\}^{\frac{1}{2}}. \qquad (3)$$

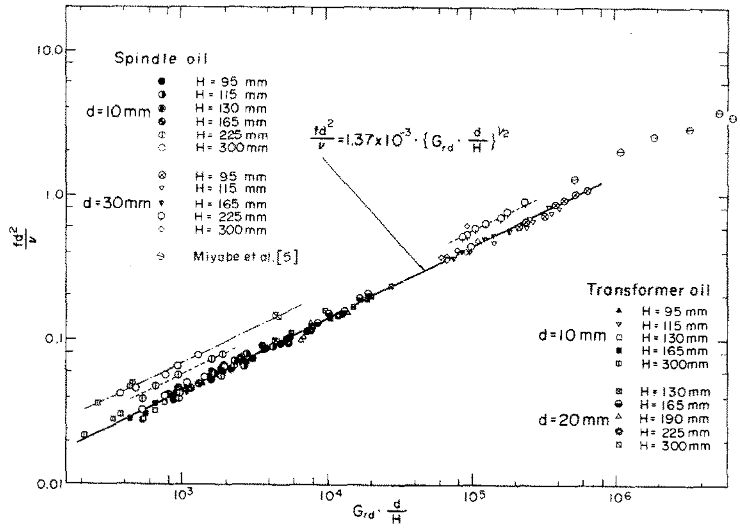

FIG. 2. Correlation between fd^2/ν and $G_{rd}d/H$.

Temperature variation

Temperature variation for transformer oil in the case of $d = 10$ mm, $H = 130$ mm and $Q = 15.4$ W/m is shown in Fig. 1. In this figure, t_l represents the temperature measured at a position of the heated surface and t_s at the position apart from the surface as mentioned above. It is obvious that the period of t_l agrees exactly with that of t_s. Referring to t_l, a large amplitude appears distinguishably as the plume passes by the measuring position, while a small one as it aparts from or approaches there.

Let us suppose that a plume, being balanced at its initial equilibrium position, is forced to shift to another position on the surface by some sudden disturbance. Then the heat-transfer rate on both sides of the new shifted position of the plume becomes unbalanced. As a result, the difference between surface temperature and then the difference between buoyancy force on both sides of the plume at its new position are induced. So the plume should be reversed towards the initial position by the resulting pressure difference in a horizontal direction. However, the plume is moved beyond the initial position by its horizontal inertia force. In such a way the plume might begin to oscillate and sway.

Frequency of swaying plume

The experimental result that the swaying motion of the plume looks like a harmonic one may permit an assumption that the abovementioned pressure difference corresponding to a restoring force is to be proportional to x, a displace-

For $H \geqslant 225$ mm, the frequency is easily affected by flow mode, and its behavior is quite similar to the doubled frequency of oscillation in Bénard type convection flow as Krishnamurti [6] reported. Data by Miyabe *et al.* [5], are for 27.1 mm in diameter and 100 mm in distance from the center of cylinder to the liquid surface.

REFERENCES

1. E. H. Bishop and C. T. Carley, Photographic studies of natural convection between concentric cylinders, *Proc. Heat Transfer Fluid Mech. Inst.*, pp. 63–78. Stanford University Press, Stanford (1966).
2. E. H. Bishop, C. T. Carley and R. E. Powe, Natural convective oscillatory flow in cylindrical annuli, *Int. J. Heat Mass Transfer* **11**, 1741–1752 (1968).
3. R. J. Forstrom and E. M. Sparrow, Experiments on the buoyant plume above a heated horizontal wire, *Int. J. Heat Mass Transfer* **10**, 321–331 (1967).
4. T. Fujii, I. Morioka and H. Uehara, Buoyant plume above a horizontal line heat source, *Int. J. Heat Mass Transfer* **16**, 755–768 (1973).
5. K. Miyabe and T. Katsuhara, Experimental investigation of the swaying plume above a heated horizontal cylinder, *Mem. Kyushu Inst. Technol.* No. 2, 9–22 (1972).
6. R. Krishnamurti, On the transition to turbulent convection, Part 2, The transition to time dependent flow, *J. Fluid Mech.* **42**, 309–320 (1970).