TEMPERATURE DISTRIBUTION IN NON-ISOTHERMAL CONDENSATION

by G. K. AGRAWAL, *Department of Mechanical Engineering, Government Engineering College, Ujjain*

(*Received* 17 *August* 1977; *after revision* 9 *February* 1978)

Nusselt's theory of laminar film condensation was developed for condensation on isothermal vertical and inclined plates and the outside of a horizontal tube. Experiments show that it is practically impossible to maintain an isothermal condensing surface.

INTRODUCTION

In this paper condensation on a horizontal tube cooled by a fluid stream is considered. The variation of the coolant temperature and the outside surface temperature is calculated. The usually neglected temperature drop due to the molecular-kinetic mass transfer in change of phase is also taken into account.

NOMENCLATURE

c	=	specific heat of coolant KCal.kg^{-1} °C^{-1}
hj, hc, h	=	interfacial coefficient of heat transfer (KCal.hr^{-1}, m^{-2} °C^{-1}); of condensing vapour; between coolant and wall.
m	=	rate of mass flow of coolant (kg/hr)
q	=	rate of heat flow (KCal. hr^{-1})
r	=	tube radius (m)
t	=	temperature (°C)
U	=	overall coefficient of heat transfer (KCal.hr^{-1}, m^{-2} °C^{-1})
X	=	distance along condensing surface (m)
X'	=	reduced non-dimensional distance

Subscripts

c	;	coolant conditions
i	;	inlet conditions of coolant
o	;	outlet conditions of coolant
s	;	condensing surface
v	;	Vapour saturation condition.

THEORY

The coefficient of heat transfer, h, between the coolant and the wall is assumed uniform all over the surface. The condensing surface temperature t_s is constant, at a cross section but varies from one section to another.

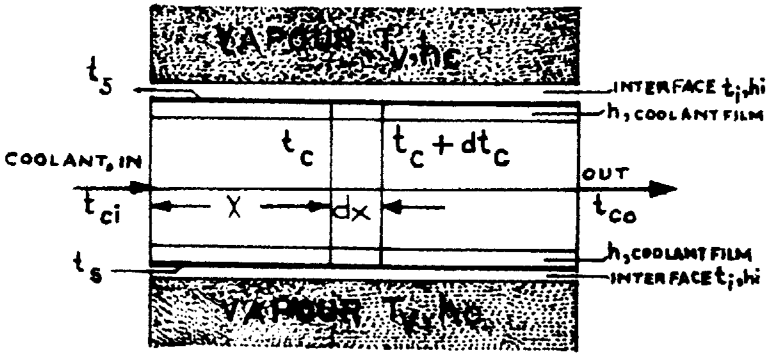

FIG. 1. Condensation on a horizontal tube cooled by a fluid stream.

Considering a ring at a distance X from the inlet end of the tube, the heat balance gives (neglecting resistance in the wall), following the approach of (Hassan *et al.* 1958),

$$\overset{(1)}{hc\,(t_v - t_i)} = \overset{(2)}{hi\,(t_i - t_s)} = \overset{(3)}{h\,(t_s - t_c)}$$

$$\pi Dh\,(t_s - tc) = mc\,\frac{dt_c}{dx} \qquad \ldots(4)$$

From (1) and (2)

$$t_i = \frac{hc\,t_v + hi\,t_s}{(hi + hc)} \qquad \ldots(5)$$

From (2) and (3)

$$hi\,(t_i - t_s) = h\,(t_s - t_c)$$

Substituting for t_i from (5), we get

$$t_s = \frac{hct_v + ht_c + (hhc\;t_v/hi)}{h + hc + (hhc/hi)} \qquad \ldots(6)$$

From (4)

$$t_s - t_c = (mc/\pi\,Dh)\,\frac{dt_c}{dx}.$$

Substituting for t_s from (6), we get

$$\frac{hc\,(t_v - t_c)}{h + hc + (hhc/hi)} = \frac{mc}{\pi\,Dh}\;\frac{dt_c}{dx} \qquad \ldots(7)$$

Integrating

$$\text{or} \int_0^{X} \frac{dx}{1 + \frac{h}{hi} + \frac{h}{hc}} = \int_{tci}^{tc} \frac{mc}{\pi Dh} \frac{dt_c}{(t_v - t_c)} \qquad \ldots(7)$$

$$\text{or} \left[1 + \frac{h}{hi} + \frac{h}{hc} \right] \left(\frac{mc}{\pi Dh} \right) \log \left(\frac{t_v - t_c i}{t_v - t_c} \right) + C = X$$

At $X = 0$ and $t_c = t_c i$. Hence $C = 0$.

$$\text{Hence} \quad \frac{t_v - t_c}{t_v - t_c i} = \exp \left[\frac{-\pi D.X}{mc \left(\frac{1}{h} + \frac{1}{hi} + \frac{1}{hc} \right)} \right] \qquad \ldots(8)$$

$$\text{Also } t_c = t_v - (t_v - t_c i) \exp \left[\frac{-\pi DX}{mc \left(\frac{1}{h} + \frac{1}{hi} + \frac{1}{hc} \right)} \right] \qquad \ldots(9)$$

Substituting for t_c from (9) into eqn. (6) and simplifying gives

$$\frac{t_v - t_s}{t_v - t_c i} = \frac{1}{1 + \frac{1}{(h/hc) + (h/hi)}} \exp \left[\frac{-\pi DX}{mc \left(\frac{1}{h} + \frac{1}{hc} + \frac{1}{hi} \right)} \right] \qquad \ldots(10)$$

$$\frac{1}{U} = \frac{1}{h} + \frac{1}{hc} + \frac{1}{hi}$$

$$X' = \frac{X}{mc/\pi DU} \quad \text{(dimensionless reduced distance)}$$

$$\text{Hence from (8),} \quad \frac{t_v - t_c}{t_v - t_c i} = e^{-X'} \qquad \ldots(11)$$

and from (10)

$$\frac{t_v - t_s}{t_v - t_c i} = \frac{1}{1 + \frac{1}{(h/hc) + (h/hi)}} e^{-X'} \qquad \ldots(12)$$

If $hi = \infty$, it refers to non-Resistance at the interface.

$$\frac{t_v - t_s}{t_v - t_c i} = \frac{1}{1 + \left(\frac{hc}{h} \right)} e^{-X'}$$

If $h = \infty$, it refers to non-resistance by coolant film.

$$\frac{t_v - t_s}{t_v - t_{ci}} = e^{-X'} = \frac{t_v - t_c}{t_v - t_{ci}}$$ i.e., the surface and coolant will assume the

same temperatures which is obvious.

The temperature distributions are shown in Figs (2 to 5)

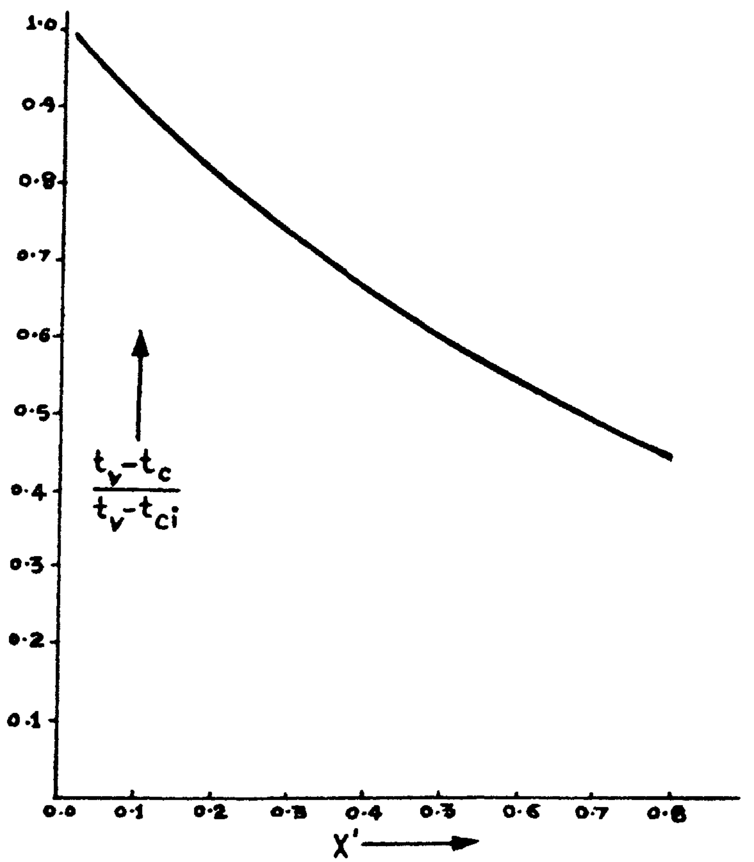

FIG. 2. Coolant temperature distribution along the tube length.

CONCLUSIONS

Examining the temperature distributions, various conclusions can be drawn;

1. Fig. (2) indicates gradual fall of $(t_v—t_c)$ along the tube length i.e., the coolant temperature will be rising as it flows along the tube, which is quite obvious.

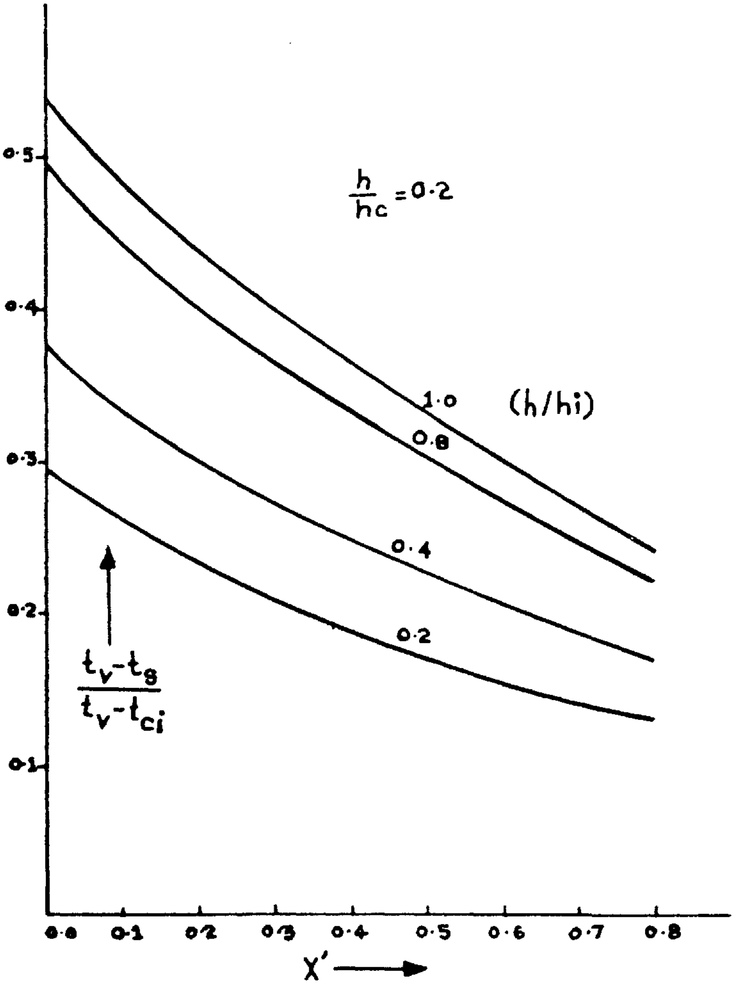

FIG. 3. Outside Surface temperature distribution along the tube length.

2. As the coolant exhibits higher resistance to heat transfer i.e. less heat transfer coeff; $\frac{h}{hc}$ will be decreasing which indicates relatively flat curves (Figs. 2, 3, 4 and 5) i.e., the surface will assume temperatures closer to the vapour temperature, conversely, with increase of conductance between coolant and wall the temperatures of surface and vapour will be markedly different.

3. As the film conductance increases relatively to coolant film coefficients, the temperature differential ($t_v - t_s$) is relatively flat. Such a situation occurs in surface steam condensers where the condensing vapour has higher conduct-

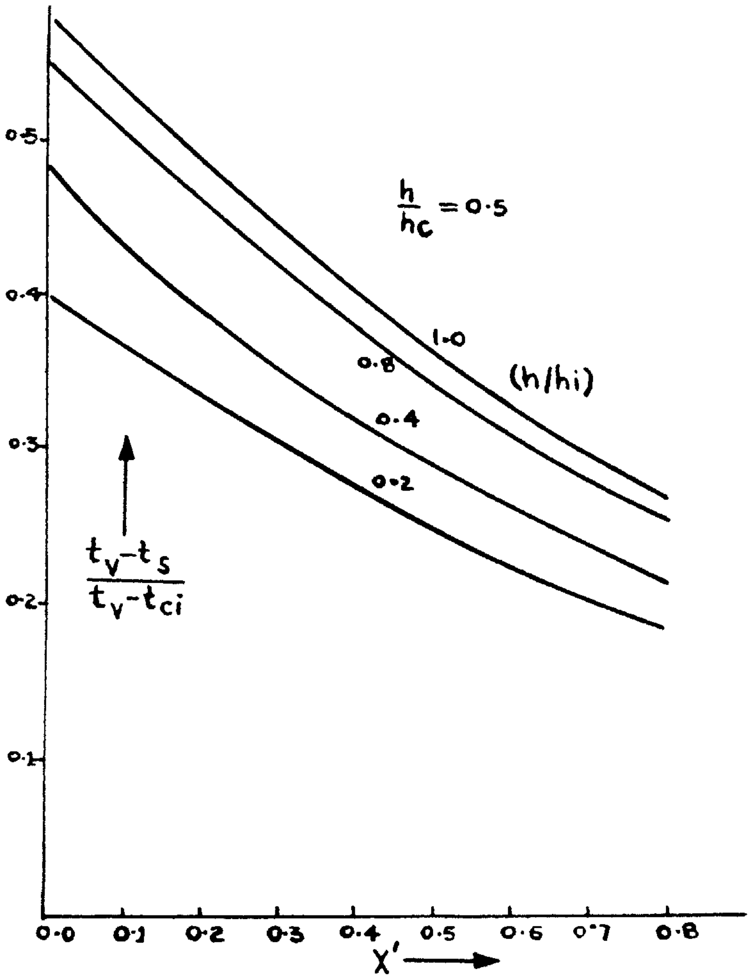

FIG. 4. Outside Surface temperature distribution along the tube length

ance relative to coolant film (which exhibits higher resistance) the surface and vapour temperatures should be coming closer. In process heating with condensing steam also such situation may occur. Care must be taken in not using Nusselt's equation for calculating heat transfer coefficients which assume an isothermal surface.

4. With decrease of interfacial heat transfer coefficients (as may be found with decreasing pressure in condensers) the vapour and surface temperatures differential will increase.

   The curves exhibits temperature distribution of coolant and condensing surface in process heating with steam or operation with high vacuum surface steam condensers.

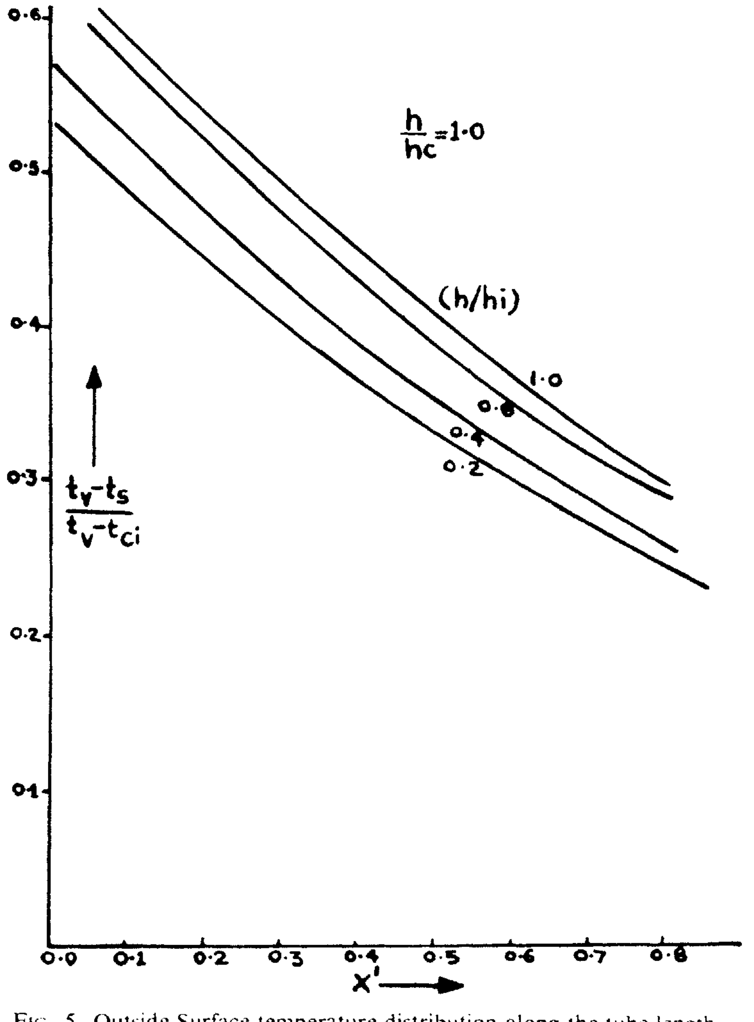

FIG. 5. Outside Surface temperature distribution along the tube length.

REFERENCE

Hassan, Kamal, Eldin (1958). Laminar film Condensation of pure saturated vapours at rest on non-isothermal surfaces. *ASME Paper*, No. 58-A, 232.