TEMPERATURE DISTRIBUTION OVER THE CROSS SECTION OF LIQUID HEAT TRANSFER FILMS

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The temperature profiles over the cross sections of vertically flowing films of water and aqueous solutions have been directly measured. It is shown that even in the wall boundary layer heat is transported not only by molecular heat conduction but also as a result of the mixing action of the waves, which increases with increase in flow density and film path.

Recent interest in the hydrodynamics and heat transfer of film flow has led to efforts to study and intensify the heat transfer between a wall and a heated film and to the need to clarify that heat transfer mechanism and its response to various conditions, so as to permit the selection and control of optimal operating regimes in film heat exchangers. Accordingly, it is necessary to determine the nature of the temperature distribution over the cross section of a film flowing by gravitation over a vertical surface as a function of the flow density and the film path.

This temperature distribution was first studied theoretically by Dukler [4], who suggested that in the practical range of values of the film Reynolds number Re_f it is impossible to neglect either the turbulent or the laminar part of the film. The author also assumed that neither of these two forms of motion exists in a film in pure form and, moreover, that a transition regime is always observed over a considerable part of the film. Then the heat flux at an arbitrary point of the film cross section y is equal to

$$q = - (\lambda + \varepsilon_n c_p \rho) \frac{dt}{dy},$$ (1)

where ε_n is the so-called turbulent thermal conductivity, for determining which the author proposes to use either Deissler's equation or Karman's equation [4] depending on the distance from the wall. This equation makes it possible to calculate the temperature distribution over the thickness of the film.
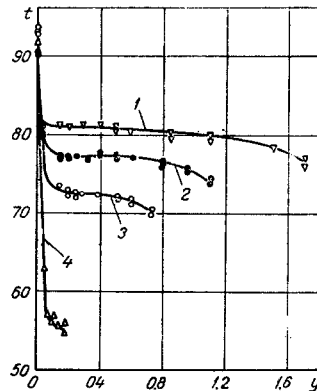
Temperature profiles in cross section of water film at various Reynolds numbers Re_f and mean free path of film x_D: : 1) Re_f = 16 253, x_D = 545 mm; 2) 101 857 and 355; 3) 4684 and 355; 4) 1306 and 200.

Previously, the temperature profile over the film cross section was measured directly by Wilke [5], who used a special displaceable vessel to partially remove the liquid film from the irrigated surface of a tube. Although, as the investigator himself remarks, his method of measuring the local temperatures is not sufficiently reliable, he was still

able to obtain the temperature profile for a diethylene glycol film in the region of small Reynolds numbers ($Re_f \leq 82$) and to draw certain general conclusions. Wilke noted two regions on the measured temperature profile: a boundary layer and a region with approximately constant temperature because of the mixing action of the waves.

We have measured the temperature profiles over the cross section of films of water and aqueous solutions of sodium chloride in the region of the high flow densities ($1300 \leq Re_f \leq 17\,000$) usually encountered in industrial practice. The experimental apparatus, the specially developed probe and the method of measuring the local temperatures and film thicknesses were previously described in [1-3]. The measured temperature profiles of the water film at various Reynolds numbers and film paths x_p are presented in the figure, from which it is clear that in the region of high flow densities all the measured temperature profiles have two characteristic regions: a boundary layer at the wall and a region at approximately the same temperature. The thickness of the boundary layer is only slight (up to 0.06 mm) and decreases with increase in Reynolds number. The temperature of the outer surface of the tube wall ($y = 0$), measured with copper-constantan thermocouples imbedded in the tube wall near the point at which the temperature profile was measured, begins to fluctuate somewhat upon the appearance of rapidly incident waves of large amplitude (curves 1, 2, 3). This is because the turbulence-generating effect of the waves is so great that the wave eddies reach the surface of the wall destroying the liquid boundary layer.

The intense mixing, observed even in the region of the film thickness, δ_t, measured in the troughs of the waves, causes a considerable fluctuation of the local film temperature, which increases as the junction of the probes is moved away from the wall. We measured only the extreme values of the local temperature fluctuations, directly from the deflections of the light spot of an optical galvenometer; these values were then averaged.

A certain decrease in the local temperatures in the region of the waves themselves $y = \delta_c - \delta_t$ (film thickness measured at the highest wave crests δ_c and in the troughs δ_t) is attributable to the fact that the junction of the probe was washed only periodically by the waves and, naturally, the temperature fluctuations increased even more, since in the intervals between waves the junction was in contact with the air.

Thus, in developed wave flow the mixing effect of the waves is so great that the local temperatures over the cross section of the film are approximately constant outside a relatively thin boundary layer. Even in this boundary layer, however, heat is transported not only by molecular heat conduction but also as a result of the mixing effect of the wave eddies. As wave flow develops (as a result of increasing flow density and film path), the wave mixing effect is intensified.

NOTATION

c_p—specific heat of the liquid at its mean temperature, $J/kg \cdot deg$ (kcal/kg $\cdot$ deg)
t—local temperature of the film, deg
q—specific heat flux, W/m^2 (kcal/m$^2 \cdot$ hr)
x_p—film path, m (mm)
y—distance from the outer surface of the wall, m (mm)
Γ_v—volume flow density, m^2/sec
δ_c—film thickness measured at the highest wave crest, m (mm)
δ_t—film thickness measured in the wave trough, m (mm)
λ—thermal conductivity of the liquid, $W/m \cdot deg$ (kcal/m $\cdot$ deg $\cdot$ hr)
ρ—density of the liquid, kg/m^3
ν—kinematic viscosity of the liquid, m^2/sec
$Re_f = 4\Gamma/\nu$—Reynolds number for film flow

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10 January 1968

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