TRANSVERSE TEMPERATURE PROFILE ACROSS LIQUID FILMS DURING DOWNWARD FLOW

K. R. Das, Yu. M. Tananaiko,
and I. I. Chernobyl'skii*

UDC 536.242:532.62

Results are shown of an experimental study concerning the transverse temperature profile of downward flowing films of liquids, pure or containing surface active additives. The results are compared with those of other authors.

In order to establish the optimum operating mode of film-flow heat exchangers and to design the heating surface, it is necessary to know the mechanism of heat transfer in the film and this in turn requires that the transverse temperature profile across the film be known.

During transition from laminar flow to undular flow and then to turbulent flow (Reynolds number $\mathrm{Re}_f = 1600\text{-}2000$) there occur turbulent fluctuations in the film which diminish towards the free surface. The liquid particles undergo intensive mixing and heat transfer is effected not only by molecular heat conduction but also by turbulent heat conduction. Moreover, surface waves generated in the process cause an intensive stirring of the liquid.

The temperature profile of a film was determined for the first time by A. E. Dukler [1], who solved on a computer the fundamental equation of heat transfer across a film. The transverse temperature profile of downward flowing films was measured by W. Wilke [2], who established the existence of two regions: a boundary layer and a constant-temperature zone, the latter affected by surface waves. The measurements of the temperature profile by that method distorted, however, the velocity profile of the film. Of interest are the data in [3] pertaining to high trickle rates ($1300 < \mathrm{Re}_f < 17{,}000$). In those tests the local temperatures across a transverse section were found by averaging the temperature oscillations at a given point (based on the deflection of the light spot of an optical galvanometer). The distortion of the velocity profile was minimized here by the use of thin thermocouples. These tests have shown that the stirring action of waves makes the boundary layer thin and the local temperatures across a transverse section approximately constant outside the boundary layer.

There are no data available on the temperature profile of a liquid film containing surface active additives.

In order to obtain reliable quantitative characteristics, the authors improved the method of temperature measurements with the readings recorded on strip charts. The test apparatus had been described earlier in [4-6]. The tests were performed with water and with aqueous solutions of sulfanol as the surface active additive (in concentrations c from 0.1 down to 0.01%). The distance between the free film surface and the pipe wall was recorded accurately by means of a model ÉO6M cathode-ray oscillograph. With the aid of a micrometer screw, the thermocouple junction (diameter $d \approx 0.08$ mm) in the probe was placed at several specific points between the wave crest and the pipe wall. The local temperatures were recorded on a strip chart of a model ÉPP-093M electronic potentiometer with 5 mV divisions.

A typical strip recording of local temperatures across a transverse film section is shown in Fig. 1 for two values of the Reynolds number: $\mathrm{Re}_f = 1630$ and 6800. The average local temperature t_f at a point in the film at a given distance from the wall was found by graphical integration. The maximum amplitude of t_f oscillations was defined as the difference between a temperature peak t_{max} and t_f on the chart.

---

*Deceased.

Polytechnic Institute, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 24, No. 5, pp. 820-823, May, 1973. Original article submitted September 26, 1972.

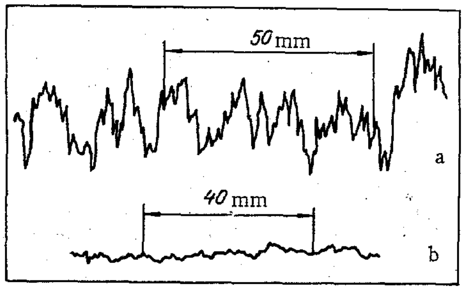

Fig. 1

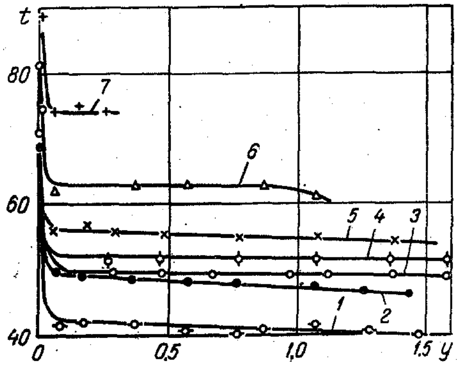

Fig. 2

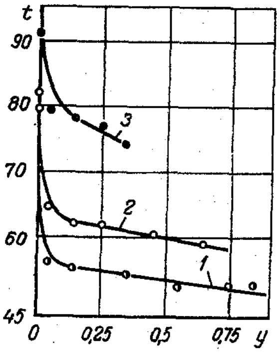

Fig. 3

Fig. 1. Recording of local temperature at a transverse section across a water film: (a) $y = 0.25$ mm, $\mathrm{Re}_f = 1630$, $x_{fp} = 200$ mm, $t_f = 74.25°\mathrm{C}$, $t_{max} = 78.3°\mathrm{C}$; (b) $y = 0.75$ mm, $\mathrm{Re}_f = 6800$, $x_{fp} = 200$ mm, $t_f = 47.5°\mathrm{C}$, $t_{max} = 48.1°\mathrm{C}$.

Fig. 2. Temperature profiles of a transverse section across a downward flowing water film, with $\mathrm{Re}_f = 6800$ and $\bar{t}_f = 54.3°\mathrm{C}$: 1) $x_{fp} = 45$ mm, 2) 200 mm, 3) 355 mm, 4) 540 mm; 5) $\mathrm{Re}_f = 7200$, $\bar{t}_f = 58.1°\mathrm{C}$, $x_{fp} = 200$ mm; 6) $\mathrm{Re}_f = 4250$, $\bar{t}_f = 57°\mathrm{C}$, $x_{fp} = 200$ mm; 7) $\mathrm{Re}_f = 1630$, $\bar{t}_f = 66.8°\mathrm{C}$, $x_{fp} = 200$ mm; distance from wall y (mm), temperature t (°C).

Fig. 3. Temperature profile of a transverse section of a downward flowing film with surface active material dissolved in water ($c = 0.03\%$), $x_{fp} = 200$ mm: 1) $\mathrm{Re}_f = 5450$ and $\bar{t}_f = 52.5°\mathrm{C}$, 2) $\mathrm{Re}_f = 4280$ and $\bar{t}_f = 56.8°\mathrm{C}$, 3) $\mathrm{Re}_f = 1178$ and $\bar{t}_f = 66.8°\mathrm{C}$; temperature t (°C), distance y (mm).

Temperature profiles of a water film are shown in Fig. 2 for various values of the Reynolds number and for various lengths of the film path x_{fp}. An analysis of these curves indicates two distinct regions in a film, regardless of the Reynolds number Re_f and of the path length x_{fp}.

1. A boundary layer with the major temperature gradient and of a very small thickness (0.05 mm, according to our method of measurement).

2. An outer layer across which the variation of local temperature is insignificant.

The shape of curves 1-4 indicates the general trend that, as the film path x_{fp} becomes longer, the temperature gradient decreases somewhat in the boundary layer as well as in the outer zone, which can be explained by a higher absolute temperature of the film after the latter has traveled a longer path.

The trickle rate (or the Reynolds number) has no noticeable effect on the transverse temperature profile of the film, although at lower trickle rates the boundary layer becomes somewhat thicker. Analyzing the recorded charts of local temperatures, we note that a drop in the trickle rate results in a much larger amplitude of temperature oscillations. Thus, at $\mathrm{Re}_f = 6800$ ($x_{fp} = 200$ mm and $y = 0.75$ mm) the maximum oscillation amplitude $t_{max}-t_f$ is about 0.6°C, while at $\mathrm{Re}_f = 1630$ it is equal to 4°C (with the same path length). This can be explained by the instability of a film at low trickle rates. Another cause of a reduced amplitude of temperature oscillations at higher values of the Reynolds number is that turbulent fluctuations may attenuate the flow waves, the scale of those fluctuations being of the same order of magnitude as the likely wave lengths.

The wall temperature was also measured near a given film cross section. No oscillation of the wall temperature was noted in any of the tests. The oscillation of local temperatures in the film was quite wide beyond $y = 0.05$ mm from the wall, at all values of the Reynolds number, although the probe recorded some decrease in this amplitude as the wall was approached. Thus, temperature oscillations were attenuated here in the boundary layer. Even in the boundary layer, therefore, heat transfer was effected here not only by molecular heat conduction but also by attenuated oscillations (convective heat transfer), as other authors too had found in their experiments [2, 3].

As the path length of a film increased, so did the oscillation amplitude of local temperatures. Thus, at $y = 0.75$ mm and $\mathrm{Re}_f = 6800$ the maximum amplitude increased from 0.55 to 2.2°C as the path length x_{fp} increased from 50 to 540 mm. This could be explained by a stronger stirring action of the waves over a longer path.

The temperature profile of a film of an aqueous sulfanol solution (concentration of the surface active additive $c = 0.03\%$) is shown in Fig. 3. The graph indicates that, with an addition of surface active material, there appears a large temperature gradient outside the boundary layer and that this gradient increases further with decreasing trickle rate. An analysis of the recorded charts of local temperatures leads to the conclusion that, at a given flow rate, the amplitude of temperature oscillations in a solution of surface active material is much lower than in pure water. An explanation for this could be the weaker stirring action of the waves in the presence of surface active material.

NOTATION

c	is the concentration of surface active material, % (mass);
t_{max}	is the maximum local temperature in the film, °C;
t_f	is the average local temperature in the film, °C;
$\overline{t_f}$	is the average temperature in the film, °C;
x_{fp}	is the length of the film path, m (mm);
y	is the distance from the wall, m (mm);
Γ_V	is the volume rate of trickle, m^2/sec;
ν	is the kinematic viscosity, m^2/sec;
$Re_f = (4\Gamma_V/\nu)$	is the Reynolds number for film flow.

LITERATURE CITED

1. A. E. Dukler, Chem. Engrg. Progress, 55, No. 10 (1959).
2. W. Wilke, VDI Forschungsheft [German], No. 490, 1-36 (1962).
3. E. G. Vorontsov, Inzh. Fiz. Zh., 15, No. 3 (1968).
4. I. I. Chernobyl'skii, Yu. M. Tananaiko, and E. G. Vorontsev, in: Chemical Apparatus Design [in Russian], Izd. Tekhnika, Kiev (1965), Vol. 2, p. 125.
5. Yu. M. Tananaiko, Khim. Promyshl., No. 4, 50 (1965).
6. R. D. Koneru, V. G. Merzlikin, Yu. M. Tananaiko, and I. I. Chernobyl'skii, Vestnik Kievsk. Politekh. Inst., Ser. Khim. Mashinostr. i Tekhnol., No. 9, 13-14 (1972).