

NOTATION

V, volume; S, area; t, τ ; P, p; T, θ ; u, v; Q, q, dimensional and dimensionless time, pressure, temperature, TIM decomposition rate, and heat flux; γ , adiabatic exponent; R, gas constant; ρ , density; H, specific enthalpy; c, specific heat; λ , thermal conductivity; α , β , θ_s , dimensionless complexes; ϵ , coefficient expressing the radiative properties of the gas medium and the heat-transfer surface; σ , Stefan-Boltzmann constant. Indices: 0, initial state and scale factors; s, surface; Π , coke; M, TIM material; P, pyrolysis front; A, ablation front; v, volatile degradation products; a, adiabatic conditions; c, completion of discharge.

LITERATURE CITED

1. I. A. Charnyi, Principles of Gas Dynamics [in Russian], Moscow (1961).
2. L. G. Loitsyanskii, Mechanics of Liquids and Gases [in Russian], Moscow (1970).
3. Mastanayakh, Teploperedacha, 98, No. 1, 152-157 (1976).
4. Yu. V. Polezhaev and F. B. Yurevich, Thermal Protection [in Russian], Moscow (1976).
5. V. P. Mugalev, Heat and Mass Transfer, Vol. 1 [in Russian], Minsk (1968), pp. 32-37.
6. N. N. Kalitkin, Numerical Methods [in Russian], Moscow (1978).
7. V. P. Isachenko, V. A. Osipova, and A. S. Sukomel, Teploperedacha, Moscow (1981).

TEMPERATURE JUMP ACROSS A PLANE INTERFACE FOR A PHASE TRANSITION IN A PURE LIQUID

A. P. Osipov, M. G. Semena, and Yu. Yu. Sergeev

UDC 536.42

We develop a theoretical model of the development of a temperature jump across the boundary between phases during a phase transition in pure liquids.

The temperature is the same across a plane boundary between the liquid and gas phases if there is no evaporation or condensation.

In order to maintain the stability of the processes of evaporation or condensation there must be a difference between the temperatures of the vapor and liquid at the boundary between the phases. This difference is usually referred to as a temperature jump in the literature. The temperature jump across the boundary between the phases is usually small: according to the data of [1, 2] it is of order of a tenth or a hundredth of a degree and hence it is neglected in engineering calculations of heat-exchange devices.

A theoretical calculation of the temperature jump has not been given in the literature, while the experimental data contradict one another [1-3]. However, general considerations and the experimental data both suggest that the temperature jump in the presence of a phase transition will increase as the vapor pressure drops, all other things being equal. This fact is important in the operation of heat-exchange devices such as a heat pipe operating at comparatively low pressure. Hence a theoretical calculation of the temperature jump in the presence of evaporation or condensation is a problem of current interest.

We consider the condensation of a pure vapor onto a liquid surface. A schematic diagram of the process is shown in Fig. 1.

For condensation the surface of the liquid must always be somewhat colder than the vapor. In this process some of the molecules of the liquid leave the surface and go into the vapor; we let G_2 be the corresponding mass flux. A mass flux G_v of vapor molecules approaches the interface 1-1, and there is a mass flux of molecules G_1 passing into the liquid.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 5, pp. 793-797, May, 1988.
Original article submitted February 17, 1987.

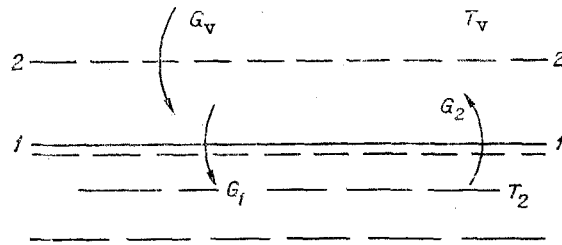


Fig. 1. Schematic diagram of the condensation process: 1-1 (solid line): boundary between the phases; 2-2 (dashed line): arbitrary surface near the boundary between the phases.

Hence close to the surface 1-1 we have a layer of vapor bounded by a surface 2-2 and we write down the balance equations for the quantity of vapor and energy for this layer. In addition, we can assume that half of the interface is filled by the flux G_1 and half by the flux G_2 . The pressures P_1 and P_v of the liquid and vapor can be taken to be equal, while the pressure P_2 can be expressed in terms of the vapor pressure P_v and the temperature T_2 with the help of the Clausius-Clapeyron equation. The fluxes G_1 and G_2 can be expressed in terms of the area of the interface F_0 , the number of molecules per unit area, and their thermal velocities. Here it is necessary to take into account that only 1/3 of the molecules are moving toward the surface.

The formulation discussed above leads to the following system of equations:

$$G_v + G_2 - G_1 = 0, \quad (1)$$

$$G_v T_v + G_2 T_2 - G_1 T_1 = 0, \quad (2)$$

$$F_1 = F_2 = \frac{F_0}{2}, \quad (3)$$

$$P_1 = P_v, \quad (4)$$

$$P_2 = P_v \exp - \frac{r}{RT_v} \left(\frac{T_v}{T_2} - 1 \right), \quad (5)$$

$$G_1 = \frac{F_0}{2} \frac{1}{3} \frac{P_1}{RT_1} \sqrt{KRT_1}, \quad (6)$$

$$G_2 = \frac{F_0}{2} \frac{1}{3} \frac{P_2}{RT_2} \sqrt{KRT_2}. \quad (7)$$

From (1), (6), and (7) we obtain

$$G_v = \frac{F_0}{6} \left(\frac{P_1}{RT_1} \sqrt{KRT_1} - \frac{P_2}{RT_2} \sqrt{KRT_2} \right), \quad (8)$$

and from (2), (6), and (7) we have

$$T_1 = \frac{G_v T_v + G_2 T_2}{G_1} = \frac{G_v T_v + \frac{F_0}{6} P_2 \sqrt{\frac{KT_2}{R}}}{\frac{F_0}{6} P_1 \sqrt{\frac{K}{RT}}},$$

and therefore

$$T_1 = \left(\frac{G_v T_v + \frac{F_0}{6} P_2 \sqrt{\frac{KT_2}{R}}}{\frac{F_0}{6} P_1 \sqrt{\frac{K}{R}}} \right)^2. \quad (9)$$

TABLE 1. Temperature Jump Calculated from (14) for Freon-22, Ammonia, and Water at Different Temperatures

Heat carrier	T_v , K	ΔT , K
Freon-22	173	0,141
	180	0,097
	210	0,0184
	240	0,006
	270	0,0029
Ammonia	198	0,018
	223	0,005
	243	0,002
	273	0,00099
	303	0,00058
Water	333	0,00043
	283	0,091
	303	0,059
	323	0,013
	343	0,006
	363	0,0035
	383	0,002

We substitute T_1 according to (9) into (8), using (4) and (5). We obtain

$$\Theta^2 + \Theta \left(\sqrt{\frac{T_2}{T_v}} + \sqrt{\frac{T_v}{T_2}} \right) \exp \left[-\frac{r}{RT_v} \left(\frac{T_v}{T_2} - 1 \right) \right] + \exp \left[-\frac{2r}{RT_v} \left(\frac{T_v}{T_2} - 1 \right) \right] - 1 = 0, \quad (10)$$

where

$$\Theta = \frac{G_v}{\frac{F_0}{6} P_v \sqrt{\frac{K}{RT_v}}}.$$

The parameter Θ characterizes the rate of the condensation process and can be called the parameter of the phase transition. In cases of practical interest we can put $\sqrt{T_2/T_v} + \sqrt{T_v/T_2} \approx 2$ in (10). Then the solution of (10) will be

$$\frac{r}{RT_v} \left(\frac{T_v}{T_2} - 1 \right) = \ln \frac{1}{1 - \Theta}. \quad (11)$$

Since the quantity Θ is much smaller than unity, the solution of (11) for T_2 can be written as

$$T_2 = \frac{T_v}{1 + \frac{RT_v}{r} \Theta}. \quad (12)$$

The temperature jump is given by

$$\Delta T = T_v - T_2 \quad (13)$$

or, using (12)

$$\Delta T = T_v \frac{\frac{RT_v}{r} \Theta}{1 + \frac{RT_v}{r} \Theta}. \quad (14)$$

Obviously (14) is also valid for the temperature jump in the case of evaporation of the liquid. In this case the parameter Θ will characterize the rate of evaporation.

The temperature jump was calculated for water, ammonia, and freon-22, using (14). The calculations were done for a heat flux density of $q = 1 \text{ W/cm}^2$ and the results are given in Table 1.

The calculated values of the temperature jump during a phase transition are not large and vary from a tenth to a hundredth of a degree for the conditions assumed here; this is consistent with the data of [2]. A decrease in the pressure of the condensation causes an increase in the temperature jump: For example, in freon-22 the quantity ΔT reaches 0.7 K for a pressure of 0.003 kg/cm².

In [4] experimental data was presented and analyzed on the thermal resistance of the phase transition for several liquids, and was represented as a so-called "condensation coefficient." Using the average value of this coefficient 0.05 (in experiments with water) and a heat flux of 2.5 W/cm², we obtain a temperature drop of $\Delta T \approx 0.01$ K, which agrees with the calculated value in Table 1 for water at $T_v = 323$ K. It should be noted that a common deficiency of practically all of the experiments is the lack of specific measures to ensure the purity of the liquids used. This should lead to a strong scatter of the values of the thermal resistance on the boundary between the phases. However, the general tendency indicates that this parameter is small (the closeness of the "condensation coefficient" to unity).

One can claim qualitative agreement for the theoretical calculation of the temperature jump across the boundary between the phases. A correct quantitative comparison could be done using the results of experiments in which sources of impurities are eliminated.

NOTATION

G_1 , mass flux of molecules of the liquid into the liquid; G_2 , mass flux of molecules of the liquid into the vapor; G_v , mass flux of vapor molecules; T_1 , vapor temperature near the liquid surface; T_2 , temperature of the liquid; T_v , vapor temperature; R , universal gas constant; c_p , c_v , specific heats; r , heat of vaporization; q , heat flux density; K , ratio c_p/c_v ; θ , parameter of the phase transition; F_0 , area of the interface; P_1 , pressure of the liquid; P_2 , phase transition pressure; P_v , vapor pressure.

LITERATURE CITED

1. M. A. Mikheev and I. M. Mikheeva, Foundations of Heat Transport [in Russian], Moscow (1973).
2. V. P. Isachenko et al., Heat Transport [in Russian], Moscow (1975).
3. P. Dan and D. Rei, Heat Pipes [in Russian], Moscow (1979).
4. L. D. Berman, Tr. NIIKhIMMASH., No. 36, 78-81, Moscow (1961).