STRATIFICATION OF A CRYOGENIC LIQUID IN A RESERVOIR IN THE CASE OF CIRCULATION COOLING

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Based on the nature of changes over time in the vertical profile of temperatures within the volume of a reservoir, we have determined the magnitude of the circulation flow and the coefficient of convection in the circulation cooling of liquid hydrogen.

Thermal stratification of a cryogenic liquid in a reservoir, governed by the external influx of heat and free convection in storage without drainage, has been the subject of earlier studies [1, 2]. In the present study we have investigated stratification in a reservoir, generated by forced circulation and the cooling of the cryogenic liquid in an external closed contour.

The study was carried out on an industrial installation (Fig. 1) in the normal course of operation on the cooling of a product prior to release to the consumer. Liquid hydrogen, stored in a spherical reservoir 1 having a diameter of 14 m with an original quantity of 60 tons ($\approx$860 m^3) at a constant pressure of 0.132 MPa and an initial temperature of 21.2 K, was drained out through tubing positioned 7 m above the lowest point of the reservoir, and it was separated into two streams. One of these was directed through throttle valve 2 into the vaporization space of recuperative cooler 3, in which a pressure of 0.034 MPa was maintained through continuous evacuation of vapors, and the liquid was brought to a boil at a temperature of 17.1 K. The second stream was injected in jet pump 4 under the working pressure of a stream of liquid hydrogen pumped out of reservoir 5 at a pressure of 1.0 MPa and a temperature gradually raised during the operation from 20.3 to 21.0 K. The resulting mixture, having a temperature of 21.9 K, was cooled to 17.4 K in the cooling coil and introduced into reservoir 1 through the lower tubing fitted out with a disk valve 6. In addition to the indicated temperatures, we also measured the temperature at three points within reservoir 1 (Fig. 2) and we measured the liquid volumes in each of the reservoirs. The liquid volume in reservoir 1 remained virtually constant, and it decreased in reservoir 5. Based on the change in volume we determined the average flow rate of the liquid out of reservoir 5 (Fig. 3).

As we can see from Fig. 2, during the circulation cooling the liquid in reservoir 1 is subjected to stratification and this is accompanied by the upward expulsion of the thermal layer by the cold and convective exchange of heat between the layers. The vertical temperature profile $T(x, \tau)$ is approximately described by the solution of the differential heat-conduction equation for the two semibounded media, exhibiting initially different temperatures and brought into contact with one another, in the presence of a time-altered coordinate contact $h(\tau)$:

$$T(x, \tau) = \frac{1}{2}\left\{T_1 + T_2 + (T_1 - T_2)\,\mathrm{erf}\left[\frac{x - h(\tau)}{2\sqrt{\varepsilon a \tau}}\right]\right\}, \qquad (1)$$

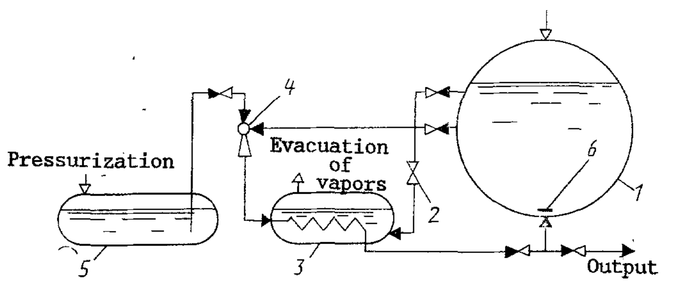

Fig. 1. Basic diagram of the installation: 1) RSV-1400 reservoir; 2) throttle valve; 3) OK-200/50 cooler; 4) jet pump; 5) RTsGV-225 reservoir; 6) disk valve.

Voronezh Technological Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 60, No. 3, pp. 425-428, March, 1991. Original article submitted April 4, 1990.

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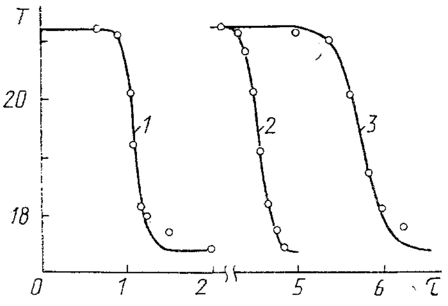

Fig. 2

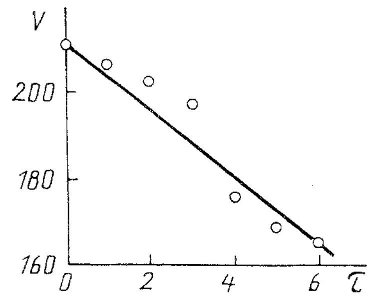

Fig. 3

Fig. 2. Measured (points) and theoretical (curves) liquid temperature in reservoir 1 at various heights: 1) 1.9 m; 2) 4.4; 3) 5.0 m. T, K; τ, h.

Fig. 3. Change in liquid volume in reservoir 5 during operation: points) measured values of the volume V; straight line) function V(τ) at a constant averaged liquid flow rate equal to $2.1 \cdot 10^{-3}$ m^3/sec. V, m^3.

$$h(\tau) = D\left\{\frac{1}{2} + \cos\left[\frac{4}{3}\pi + \frac{1}{3}\arccos A(\tau)\right]\right\}, \tag{2}$$

$$A(\tau) = 1 - 12\int_0^\tau U(\tau)\,d\tau/(\pi D^3) = 1 - 12\bar{U}\tau/(\pi D^3). \tag{3}$$

The mathematical model (1)-(3) includes the unknown parameters $\bar{U}$ and ε which we find by the method of minimizing deviations in the measured and theoretical temperatures for various fixed values of the coordinate x. The results are presented in the following table (see Fig. 2):

x, m	1,9	4,4	5,0
$\bar{U} \cdot 10^3$, m^3/sec	18	20	20
ε	10	1,0	1,6

Owing to the absence of liquid flowmeters in the installation, it proved to be impossible directly to measure the quantity U. However, $\bar{U}$ can be calculated from the heat-balance equation for the cooler, from which, without consideration of droplet entrainment, external heat influx, and energy dissipation in the coil and throttle valve, it follows that

$$\bar{U} = \bar{U}_V \frac{r - c(T_1 - T_3)}{c(T_4 - T_2)}. \tag{4}$$

Owing to the constancy of the liquid volume in reservoir 1 we assume that $\bar{U}_v \approx \bar{U}_w \approx 2.1 \cdot 10^{-3}$ m^3/sec. Substituting into (4) T_1 = 21.2 K, T_2 = 17.4 K, T_3 = 17.1 K, T_4 = 21.9 K; r = $4.6 \cdot 10^5$ J/kg; c = $9.35 \cdot 10^3$ J/(kg·K), we obtain $\bar{U}$ = $21 \cdot 10^{-3}$ m^3/sec, which is in agreement with the above-cited values. The significant role of convection for the case in which x = 1.9 m is explained by the proximity of the reservoir wall and the supply tubing. With an increase in the quantity of coolant in the reservoir we achieve a hydrodynamic regime that is nearly ideal from the standpoint of expulsion. The derived data indicate the possibility of cooling and supplying to a consumer any required portion of the product contained within the reservoir.

The method of investigation used in this study can also be applied to other industrial cryogenic systems without resort to additional special measurement apparatus.

NOTATION

a and c, coefficients of thermal diffusivity and specific heat capacity for the liquid; D, reservoir diameter; r, specific heat of vapor formation; T_1 and T_2, initial and final temperature of cooled liquid; T_3 and T_4, temperature of liquid in the vaporization state and at the inlet to the cooler coil; $\bar{U}$, time-averaged circulation flow; $\bar{U}_v$ and $\bar{U}_w$, mean liquid flow rate to the vaporization chamber and the rate of working fluid flow in the jet pump; x, instantaneous vertical coordinate reckoned from the lowest point of the reservoir; ε, coefficient by means of which to take into consideration convective heat exchange; τ, instantaneous time, reckoned from the onset of circulation.

LITERATURE CITED

1. V. P. Belyakov, *Cryogenic Engineering and Technology* [in Russian], Moscow (1982).
2. N. V. Filin and A. B. Bulanov, *Liquid Cryogenic Systems* [in Russian], Leningrad (1985).

THE HYDRODYNAMICS OF CERTAIN SURFACE PHENOMENA

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UDC 532.529

Based on wave theory, we have derived expressions to describe the hydrodynamics of certain surface phenomena. We have determined the conditions of their applicability.

In a number of branches of engineering, the course of physicochemical processes is governed by such superficial phenomena as wetting, threading, etc. The hydrodynamics of such processes is generally treated from the standpoint of viscous fluid flow [1]. On the basis of derived quantitative relationships one might assume that liquid motion is based on wave processes.

With the flow of an inviscid fluid into a vertical axisymmetric capillary a meniscus is formed at the surface of the liquid column. On the one hand (since the perimeter of the meniscus represents the line of contact for three phases, while this state is characteristic only of one end of the liquid column), we have the possibility of the development of a capillary wave having a length $\lambda_\sigma = 2\pi(\sigma/\Delta\rho g)^{1/2}$ [2]. Since this wave moves along the surface of the capillary, and the thickness r of the liquid layer is commensurate with the length of the wave, its velocity of motion will be $w_\sigma = 2\pi[\Delta\sigma r/(\rho_1 + \rho_2)]^{1/2}/\lambda_\sigma$ [2], while the velocity vector is directed upward. On the other hand, if the meniscus curvature $R_c = r/\cos\theta$, it may be treated as a capillary wave whose length is equal to the perimeter of the circle passing through the generatrix of the spherical surface of the meniscus. At the initial instant of liquid influx into the capillary, since $\theta = 0$, $R_c \to \infty$ and the velocity of the second capillary wave $w_\sigma = [2\pi\sigma/(\rho_1 + \rho_2)\lambda_\sigma]^{1/2}$ is equal to zero and less than the velocity of the first wave, i.e., the speed with which the liquid rises in the capillary is determined by the velocity of the first capillary wave. As the meniscus is formed θ and R_c diminish, the velocity of the second capillary wave increases, reaching and exceeding the velocity of the first capillary wave when $(\sigma/\Delta\rho g)^{1/2}(\cos\theta)^{1/2} \geq r$, i.e., on conclusion of the meniscus formation and satisfaction of the conditions of capillary influx. From this instant on, the velocity of the second capillary wave determines the influx process.

As soon as a liquid column of height h appears in the capillary, this column plays the role of a gravitational wave of length λ_g, equal to the perimeter of a circle of diameter h. Since the vector of velocity for the motion of the gravitational wave $w_g = [g\lambda_g(\rho_1 - \rho_2)/2\pi(\rho_1 + \rho_2)]^{1/2}$ [2] is directed downward, the resulting velocity of liquid motion in the capillary is $w_h = w_\sigma - w_g$. Thus, at the stage of meniscus formation the rate of liquid ascent w_h in the capillary is equal to the difference between the velocities of motion for a capillary wave of length $\lambda_\sigma = 2\pi[\Delta\sigma/(\rho_1 - \rho_2)g]^{1/2}$ and w_g for a gravitational wave of length $\lambda_g = \pi h$ [2]:

$$w_h \equiv \partial h/\partial\tau = 2\pi[r\Delta\sigma/(\rho_1 + \rho_2)]^{1/2}/\lambda_\sigma - [g\lambda_g(\rho_1 - \rho_2)/2\pi(\rho_1 + \rho_2)]^{1/2}. \qquad (1)$$

When we integrate expression (1) in limits of $\tau = 0$, $h = 0$ and $\tau = \tau_m$, $h = h_m$, after transformation, we find that the duration of meniscus formation amounts to

$$\tau_m = \left(\frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}\right)^{1/2}\left(\frac{r}{g}\right)^{1/2}\left[2\ln\frac{1}{1 - \left(\dfrac{1 - \sin\theta}{2\cos\theta}\right)^{1/2}} - (2)^{1/2}\left(\frac{1 - \sin\theta}{\cos\theta}\right)^{1/2}\right]. \qquad (2)$$

After formation of a meniscus with a curvature radius of $R_c = r/\cos\theta$ the velocity of motion for the inviscid liquid becomes equal to the difference between the velocity w_σ for a capillary wave of length $\lambda_\sigma = 2\pi R_c$ and w_g for a gravitational wave of length $\lambda_g = \pi h$:

Dnepropetrovsk Metallurgical Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 60, No. 3, pp. 428-432, March, 1991. Original article submitted February 7, 1990.

