DISCHARGE OF A LIQUID JET UNDER NEAR-CRITICAL THERMODYNAMIC CONDITIONS

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The behavior of a Freon-22 jet and a kerosene jet in a concurrent nitrogen stream under near-critical thermodynamic conditions is analyzed qualitatively.

The operating process in combustion chambers, in gas generators of certain type engines, and in other apparatus depends largely on the rate of liquid jet and gas stream mixing. The mixing process may occur in various modes, depending on the pressure in the chamber and on the temperatures of the components. Under some physical conditions the jet breaks down into droplets, which then disintegrate and evaporate. Under other physical conditions the jet mixes with the gas stream without droplet formation and evaporation (essentially, when the temperatures of both components are high and the pressure in the combustion chamber is high). The mixing process is governed by surface tension. In the first case, the surface tension of the liquid is retained and we speak of a two-phase jet. In the second case there is no surface tension in the liquid and we speak of a one-phase jet. In general, a jet may contain two-phase as well as one-phase mixing zones.

In [1, 2] were given the results of theoretical and experimental studies concerning a nitrogen jet at a temperature $T_0 = 80°K$ discharged into a medium of gaseous nitrogen at a temperature $T_N = 360°K$ and a pressure of $40 \cdot 10^5$ N/m^2.

Mixing of the jet with the surrounding medium is tentatively depicted on a P–V diagram by an isobar whose end points correspond to the temperature T_0 of the discharged jet and the temperature T_N of the gaseous medium, respectively.

Since the experiments were performed at a supercritical pressure, at which the $T_0 - T_N$ isobar did not cross the two-phase regions, hence the mixing of liquid and gaseous nitrogen was occurring under one-phase conditions.

This situation was confirmed by tests. On the photographs in [2] the nitrogen jet appeared gaseous.

Critical phenomena are revealed not only in single-component but also in binary mixtures. If a jet of one substance is discharged into a medium of another substance, then a binary mixture is produced in the process. The parameter levels (pressure, temperature, and concentration) at which a steady-state binary mixture appears in two phases or in one phase can be determined from phase equilibrium diagrams.

In this study the authors have examined the discharge of a Freon-22 jet and a kerosene jet into gaseous nitrogen. Phase diagrams of these pairs of substances had been obtained experimentally at the State Institute of the Nitrogen Industry. The experiments were performed on an apparatus consisting of a high-pressure tank inside a tilting furnace. Into a vacuum tank was poured any amount of Freon-22 or kerosene and then any amount of nitrogen. This mixture was subsequently heated to a given temperature. The tank pressure was set to a certain level by means of a press and was measured with a manometer. After being stirred mechanically through a special channel, the mixture was sampled off the top and off the bottom of the tank, i.e., off the liquid phase and off the vapor phase. When the liquid and the vapor

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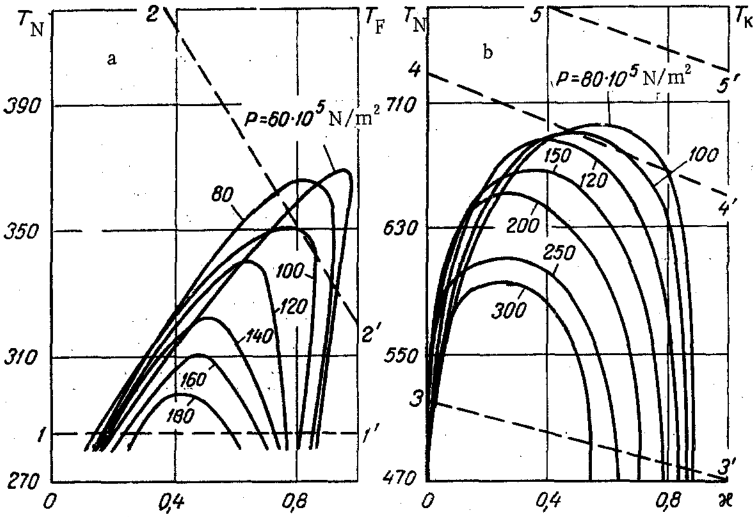

Fig. 1. Phase equilibrium diagrams of binary mixtures: a) Freon–nitrogen; b) kerosene–nitrogen.

concentration were different at some definite pressure and temperature, this indicated a two-phase mixture. When the concentrations of both components were the same at some definite pressure and temperature, however, this indicated a one-phase binary mixture. Phase diagrams of the pairs of test substances have been plotted on the basis of these results (Fig. 1). The abscissas represent concentrations of Freon-22 or kerosene in nitrogen ($\varkappa = 1$ corresponds to pure Freon-22 or kerosene), the ordinates represent temperatures. The regions above the P = const curves represent one-phase states of the mixture, the regions below these curves represent its two-phase state. The critical points on the phase diagrams of binary mixtures are those where the tangents to the isobars become horizontal. The kerosene–nitrogen phase diagram (Fig. 1b) is based on tests up to 620°K and tentative extrapolations by the authors into the higher temperature range. We note that these phase diagrams were obtained under quasisteady conditions. The use of these phase diagrams for evaluating the mixture characteristics in a jet is based on a few premises. The temperature throughout the mixing process is assumed to be a linear function of the concentration. This makes it permissible to represent the mixing process on the phase diagram tentatively by a straight line. An analysis of these diagrams indicates that it will be a one-phase mixture and the jet will be gaseous, if the process line does not intersect the respective operating-pressure isobar (straight line 2-2' for pressure $P = 120 \cdot 10^5$ N/m^2 in Fig. 1a and straight line 5-5' for pressure $P = 80 \cdot 10^5$ N/m^2 in Fig. 1b). If the process line crosses the two-phase region below the respective isobar, where surface tension forces are the essential factor in shaping the jet, then the jet behaves like a liquid one (straight lines 1-1' and 3-3' in Fig. 1a, b, respectively). If a nonlinear relation is assumed between temperature and concentration, then mixing of the jet with the surrounding medium can be represnted on the phase diagram tentatively by a curve crossing or bypassing the two-phase region, and analogous conclusions can be drawn on this basis. It is to be noted that, near a critical point, passage from the two-phase region to the one-phase region occurs smoothly and without step changes in the physical properties of the substance. Within this region the surface tension forces are negligible and a jet can be considered gaseous with a heavy admixture of separate liquid droplets.

The jet mixing experiments were performed on an apparatus shown in Fig. 2. The basic part of this apparatus was a barometric chamber in the form of a thick-walled steel cylinder 1 with an inside diameter 110 mm. Freon-22 or kerosene were poured under pressure through valve 11, flow meter 12, electric preheater 13, and into nozzle 3 with a 1.5 mm diameter, from which the jet was then discharged. In order to generate a concurrent stream, nitrogen was driven from a tank through the regulator valve 4 into coil 5, where it was heated to the necessary temperature by the combustion products exhausted from chamber 6. The hot nitrogen was then fed through flow meter 7 and honeycomb 8 into the operating zone of the apparatus. The pressure here was measured with manometer 9 and its level was set by means of the regulating needle 10. The initial jet temperature was measured with a copper–constantan thermocouple 14. The mixing of the jet with the surrounding medium was photographed through quartz glasses 2 with a high-speed movie camera 15 at a rate of 2000 frames/sec.

The purpose of these experiments was to explain how the temperature and the pressure of each component affect the jet structure, and to what extent the phase diagrams reflect the actual physical aspects of

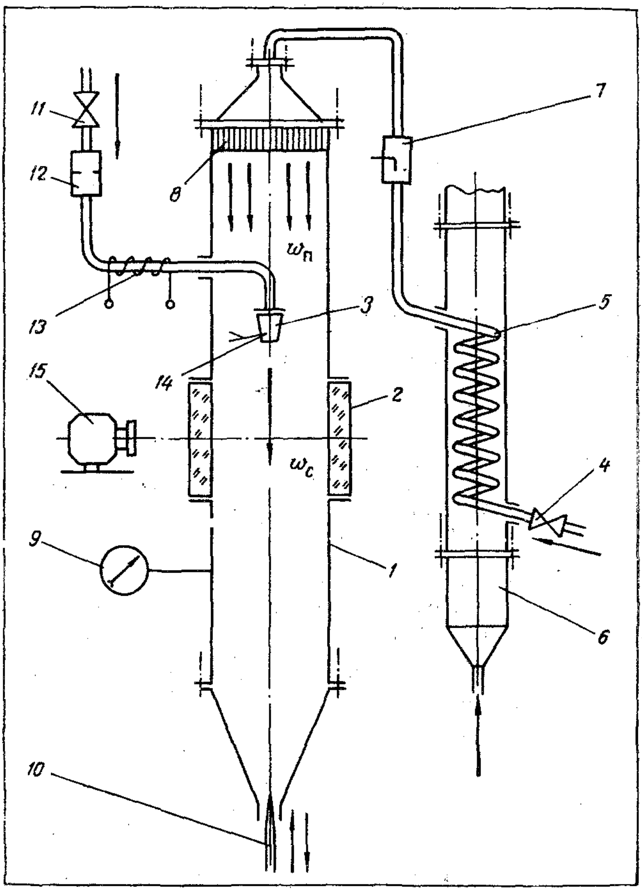

Fig. 2. Schematic diagram of the test apparatus.

the jet mixing process. In order to eliminate dynamic effects on the jet fragmentation and disintegration, the discharge velocity was adjusted to the same (3 m/sec) in all tests while the velocity of the concurrent stream was maintained at 0.3 m/sec. As has been shown in [4], at such a discharge velocity a liquid jet remains intact through an appreciable distance from the nozzle.

Moving pictures were made in the tests of Freon-22 and kerosene jets discharging into a concurrent stream of gaseous nitrogen at various chamber pressures, jet temperatures, and stream temperatures. Individual photographs are shown in Fig. 3.

In Fig. 3a is shown a photograph of the Freon-22 jet in nitrogen at a chamber pressure of $120 \cdot 10^5$ N/m^2, at initial Freon-22 and nitrogen temperatures both 285°K. The mixing of the jet is represented tentatively by the straight-line segment 1–1' in Fig. 1a, which lies almost completely within the two-phase region. In this case the surface tension forces remain almost undiminished and, therefore, such a jet should be considered liquid and this is indicated also by its external appearances.

In Fig. 3c is shown a photograph of the Freon-22 jet in nitrogen at a pressure of $120 \cdot 10^5$ N/m^2, at a Freon-22 temperature of 320°K and a nitrogen temperature of 470°K, which corresponds to segment 2-2' in Fig. 1b located completely within the one-phase region. Under these conditions there is no surface tension in the jet (Fig. 3c) and the latter has the external appearance of a gas. In Fig. 3b is shown a photograph of the Freon-22 jet at 320°K passing through nitrogen at 470°K, at a chamber pressure of $60 \cdot 10^5$ N/m^2. The mixing of this jet is represented in Fig. 1a by straight segment 2-2', which through a short distance crosses the two-phase region. Consequently, the jet parameters here are near-critical and thus the surface tension forces are weakened. In its external appearance the jet approaches both a gas and a liquid, inasmuch as it carries some quantity of droplet suspensions.

For the kerosene jet in nitrogen, the photographs Fig. 3d-f match the phase diagram in Fig. 1b. The kerosene jet was examined at a chamber pressure $P_N = 80 \cdot 10^5$ N/m^2. Additional qualitative data on the flow structure could be obtained in these tests with the aid of a Teflon barrier 40 mm in diameter placed 30 mm away from the nozzle throat. In Fig. 3d is shown a photograph of the kerosene jet in nitrogen at initial temperatures $T_K = 470$°K and $T_N = 520$°K, respectively. The mixing of this jet is represented tentatively

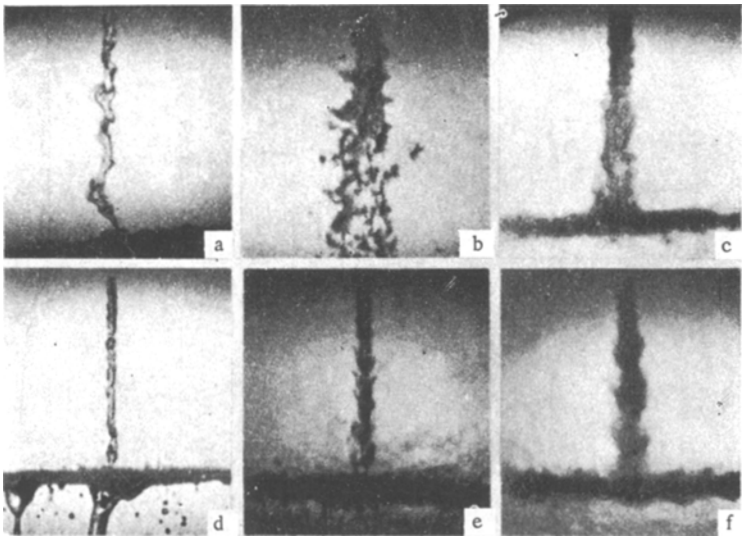

Fig. 3. Photographs of jets. Freon-22 jet in nitrogen: $P_N = 120 \cdot 10^5$ N/m², $T_N = 285$°K, $T_F = 285$°K (a); $P_N = 60 \cdot 10^5$ N/m², $T_N = 470$°K, $T_F = 320$°K (b); $P_N = 120 \cdot 10^5$ N/m², $T_N = 470$°K, $T_F = 320$°K (c). Kerosene jet in nitrogen: $P_N = 80 \cdot 10^5$ N/m², $T_N = 520$°K, $T_K = 470$°K (d); $P_N = 80 \cdot 10^5$ N/m², $T_N = 730$°K, $T_K = 650$°K (e); $P_N = 80 \cdot 10^5$ N/m², $T_N = 800$°K, $T_K = 730$°K (f).

by straight segment 3-3' in Fig. 1b, which lies completely within the two-phase region with undiminished surface tension forces. Accordingly, the kerosene jet must be liquid and this is indicated also by its external appearance.

In Fig. 3f is shown a photograph of the kerosene jet ($T_K = 730$°K) in nitrogen ($T_N = 800$°K) the mixing of which corresponds to segment 5-5' in Fig. 1b. Since this segment lies within the one-phase region where there is no surface tension, hence this jet must be gaseous and this is also indicated by its external appearance. In Fig. 3e is shown a photograph of the kerosene jet ($T_K = 650$°K) in nitrogen ($T_N = 730$°K) the mixing of which corresponds to segment 4-4' in Fig. 1b with a short portion within the two-phase region. Since the jet parameters are near-critical here, with the surface tension forces weakened, hence the jet must be intermediate between liquid and gaseous. This conclusion agrees qualitatively with the jet photographs.

It follows from the results of this study that the phase diagrams do reflect, to the first approximation the phenomenological pattern and may be used for evaluating the jet structure.

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