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STEAM-WATER CRITICAL FLOW FROM HIGH PRESSURE
SYSTEMS -- INTERIM REPORT

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SYSTEMS -- INTERIM REPORT

F. R. Zaloudek

January 30, 1964

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

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In an earlier report⁽⁶⁾, the problems associated with the prediction of the critical discharge rates of steam-water mixtures were discussed in detail. That report also gave the results of an experimental investigation of critical flows from long flow passages performed at low pressures. That investigation was later extended to consider short tubes, nozzles, and orifice flow configurations⁽⁷⁾. The present work was undertaken to experimentally investigate the critical discharge phenomenon at higher pressures and to use the data gathered to critically evaluate the various proposed critical flow models.

The purpose of this interim report is to describe in detail the apparatus assembled for this investigation and to report preliminary findings regarding the critical discharge rates from a 0.5-inch diameter flow passage.

SUMMARY

The critical discharge of steam-water mixtures from a short piece of pipe ($L/D = 20$) was studied at upstream pressures approaching 2000 psia. The pipe was 0.505-inch in diameter and had a 20-degree conical approach section. Inlet enthalpies of approximately 425, 460, 485 and 530 Btu/lb were considered. When a two-phase mixture entered the test section, flow-choking conditions were observed to occur at the end of the test section, and the data demonstrated good correspondence with the predictions of the Fauske critical flow theory⁽³⁾. When compressed water entered the pipe and was required to flash to a steam-water mixture in the length of the

pipe or in the conical approach section, the location of primary choking was observed at the entrance of the pipe rather than at the exit where it is normally assumed to exist. Flow rates were considerably greater than predicted by the Fauske theory based upon corresponding exit conditions. During the existence of upstream choking, the pressure at the entrance of the pipe was observed to remain at the saturation value regardless of flow rate. The data were correlated by the following equation with maximum deviation of 10 per cent:

$$G = C \sqrt{\frac{2g (P_{up} - P_{sat})}{v_f}} \quad (400 \leq P_{up} \leq 1800 \text{ psia})$$

where

- G = Mass velocity during upstream choking.
- P_{up} = Upstream pressure.
- P_{sat} = Saturation pressure.
- v_f = Specific volume of saturated water.
- C = 0.95.

This upstream choking was similar to the choking phenomenon observed in an earlier investigation⁽⁷⁾ in which very short tubes were considered at lower temperatures and pressures than used in the present study.

DESCRIPTION OF EXPERIMENTAL METHOD AND APPARATUS

In the present work, the experimental method employed to investigate the critical flow of steam-water mixtures at high pressures was essentially the same as that employed in the early investigations of this phenomenon at low pressures⁽¹⁾⁽³⁾⁽⁶⁾⁽⁸⁾. By this method, a steam-water mixture of

known enthalpy was caused to flow through a constant area flow passage to the atmosphere while measurements were made of flow rate and pressures along the flow passage. These pressures were extrapolated by means of numerical or graphical techniques to determine the pressure at the exit of the passage. This pressure is called the "critical pressure" and has been successfully correlated in earlier investigations with the mass flow rate and enthalpy of the steam-water mixture at the exit.

Near the exit of the flow passage, extremely rapid depressurizations have been noted⁽³⁾⁽⁶⁾⁽⁸⁾. Therefore, in order to get maximum accuracy in the extrapolation, wall pressure taps at very small intervals were necessitated.

The present program of this investigation calls for the consideration of flow passages varying in diameter from 1/2 to 2 inches and in length from 6 inches to 6 feet. At the present time, data have been obtained on only one test section. This test section was 0.505-inch in diameter and 10 inches long. Wall pressure taps 0.010-inch diameter were provided at locations approximately 0.025-, 0.060-, 0.090-, 0.125-, 0.250-, 0.500-, 1.00-, 2.00- and 8.00-inch from the discharge end.

Water or steam-water mixtures of desired enthalpy and pressure were supplied to the test section by means of the auxiliary apparatus pictured schematically in Figure 1. One of the principal pieces of equipment in this auxiliary apparatus was an insulated 1000-gallon, 2500-psi, 650°F pressure vessel in which water was pressurized, heated, and stored before discharge through the test section to the atmosphere. An air system was

provided to maintain the pressure in the vessel at a constant value during the entire "blowdown" of the water through the test section. This ability to maintain steady vessel pressures enabled steady-state experimentation and circumvented many of the transient measurement problems associated with "saturated blowdowns."

This air system consisted of a 5000-psi air compressor and two 5000-psi receivers of 124 cubic feet combined capacity. A pressure-reducing valve fed air from the receivers to the pressure vessel as required to maintain pressure in the vessel at the desired value.

The water was carried from the bottom of the vessel to the testing area by means of a four-inch schedule 160 pipe. Before the water entered the test section, its flow rate was measured by means of a calibrated Gentile flow tube. Following the flow tube was located a flash-flow valve. The purpose of this valve was to regulate the quantity of flow so that several test conditions could be investigated while maintaining constant vessel conditions. Between the valve and the instrumented test section was a length of two-inch pipe which acted to reduce the pressure disturbances originating at the valve. The transition section between the two-inch pipe and the test section consisted of a two-inch by one-inch pipe reducer, four inches of one-inch schedule 40 pipe and, finally, a conical transition passage of 20° TIA connecting the one-inch pipe to the one-half inch bore of the test section.

In preparation for a test, deaerated and deionized distilled water was injected into the vessel where it was pressurized and heated by means of

an external flow loop. This loop consisted of a pump and an electric heater which was capable of increasing water temperature at the rate of 3 to 4°F per minute.

The pressures along the test section and across the flow tube were measured by means of dc-excited strain-gage type transducers. The signals from the pressure transducers and from thermocouples installed in the pressure vessel and upstream of the flow tube were routed to a "medium speed" automatic data-acquisition system. Here, the signals were automatically analyzed, scaled, and then digitally recorded on an automatic typewriter and on punched paper tape. The speed of the data-acquisition was sufficient to enable the scan of a complete set of data in about 15 seconds. Precautions were taken to insure the continuous accuracy of the automatic-data system. These precautions included the following:

- 1) Known voltages were read automatically after each data scan to check equipment calibration.
- 2) Excitation voltages for the various transducers were stabilized by triple zener diodes and monitored continuously to assure the stability of the transducer characteristics.
- 3) Multiple transducers were employed to sense pressures of principal interest (such as the pressure across the flow meter).
4. Complete transducer calibration curves were made after every three or four runs. A dead-weight tester was used as the calibration standard.

The steam-water mixture discharged by the test section was carried by a six-inch line to a wet well. Here, the steam was condensed and the water cooled prior to discharge to the sewer. At no time during testing was the pressure downstream of the test section observed to rise above 5 psig.

The following procedure was followed in the performance of these tests:

- 1) The 1000-gallon vessel was filled with deaerated and deionized distilled water where it was pressurized and heated to the desired temperature.
- 2) After the desired temperature had been attained, the heating system was isolated from the vessel. The regulating valve between the 5000-psi air receivers and the water vessel was adjusted to produce the desired pressure in the vessel. This pressure was selected so that the pressure in the flow-measuring device would be at least 100 psi above the saturation pressure at all flow rates anticipated.
- 3) The automatic-data system was activated in a "continuous-scan" mode.
- 4) The flash-flow valve upstream of the test section was opened so as to allow the desired flow rate through the test section.
- 5) The data typed out by the automatic-data system were observed visually to determine when steady-state conditions were approached. When repeated

identical data scans were observed, the process was assumed to be at steady state. Generally, this occurred within three to five minutes of the initial valve adjustment.

- 6) After data scans were completed, the valve was readjusted to obtain another flow rate.

This entire process was repeated until the water in the vessel was exhausted. From one to four steady-state data points could be obtained with 1000 gallons of water, depending upon the conditions being considered.

Using this procedure, the critical discharge phenomenon through the 0.505-inch diameter, 10-inch long flow passage was investigated at stagnation enthalpies of approximately 425, 470, 490 and 530 Btu/lb. These enthalpies correspond to pressure vessel temperatures of about 445, 585, 500, and 535°F, respectively. The pressure in the vessel was held at either 1500 psi or 2000 psi in every case. The flow rate through the test section was controlled by means of the flash-flow valve as described earlier. This valve was adjusted so that test section mass velocities in increments of 1000 to 2000 lb/sec-sq ft could be investigated. At each equilibrium condition, the pressures indicated at the wall taps along the test section were extrapolated by graphical techniques to determine the pressure at the exit of the flow passage. This pressure was defined as the "critical pressure" corresponding to the flow rate at the equilibrium condition.

RESULTS AND DISCUSSION

The data gathered in this series of critical flow experiments is summarized in Figures 2 through 5. It was presumed that the location of the flow choking was at the exit of the test section. Accordingly, these figures reflect an attempt to correlate the data in the conventional manner by assuming the critical mass velocity a function of 1) the stagnation enthalpy (tank enthalpy), and 2) the critical exit pressure obtained by the extrapolation technique described earlier.

Each of these figures represent the data gathered for a range of stagnation enthalpies, because striation of the water in the vessel prior to its discharge through the test section prevented the close control of enthalpy. For each small enthalpy range, good correspondence between the experimental results and the predictions of the Fauske theory⁽³⁾ was obtained for critical mass velocities below a certain value. Above this value, wide divergence between theory and experiment was observed. =====

Also, in Figures 2 through 5, the pressure measured upstream of the test section is plotted as a function of observed mass velocity. Comparisons of the relationships between upstream pressure and the critical pressure for each experimental run revealed that the upstream pressure was above the saturation value in each case where there was disagreement between theory and experiment. In these cases, initial vaporization occurred within the length of the test section or in the conical approach section. Where there was agreement between theory and experiment, the existence of a two-phase flow upstream of the test was determined.

Figure 6 is a typical plot of the axial pressure profiles obtained for stagnation enthalpies in the range of 525 - 533 Btu/lb. No pressure taps were provided in the two-inch length at the entrance of the test section, and the curves shown in this region are extrapolations of the downstream pressure profiles. These curves suggest strongly that the pressure at the entrance to the test section was limited to the saturation value for all cases where a divergence from the theory occurred. Therefore, it can be concluded that, in these cases, the primary location of the choking phenomenon was at the entrance to the test section rather than at the exit where it is usually assumed to occur.

In Figure 7, it is demonstrated that all data obtained for entrance choking in the present test section can be correlated with the following equation:

$$G_c = .95 \sqrt{\frac{2g(P_{up} - P_{sat})}{v_f}} \quad (1)$$

where

- v_f = Specific volume of saturated liquid.
- G_c = Critical mass velocity.
- P_{up} = Upstream pressure.
- P_{sat} = Saturation pressure.

Maximum deviation of experimental data from this curve was less than 10 per cent.

In an earlier investigation⁽⁷⁾, critical flow in test sections with sharp leading edges was studied at low pressures. The incidence of entrance choking was observed under the same circumstances as obtained in this present study. Correlation of data was accomplished by the following equation:

$$G_c = .62 \sqrt{\frac{2g (P_{up} - P_{sat})}{v_f}} \quad (2)$$

In this earlier work, entrance choking was also observed with rounded entrance slopes but insufficient data were obtained to develop a correlation.

If equations (1) and (2) are compared, taking into consideration the type of entrances involved, an important observation can be made. Both sets of data can be represented with good accuracy by the following equation:

$$G = CF \sqrt{\frac{2g (P_{up} - P_{sat})}{v_f}}$$

where

F = Velocity approach factor.

C = Contraction coefficient for entrance shape involved.

This equation represents the maximum flow possible before choking when a liquid of pressure P_{up} and temperature T_{up} is required to flash during acceleration through a flow passage reduction. For very short tubes ($L/D < 6$) this type of relationship was observed to break down in reference (7) due to the interactions of other phenomena and greater maximum mass velocities were observed to occur in some cases.

In every critical flow condition where entrance choking was observed, a secondary choking phenomenon probably existed at the exit. By varying downstream pressure, it was found in reference (7) that, generally, a pressure differential of 100 psi between the exit of the pipe and the downstream plenum was sufficient to insure the existence of exit choking. In the present work, these pressure differentials ranged from 200 psi to 750 psi; therefore, secondary exit choking was suggested. Figures 2 through 5 show, however, that this secondary exit choking deviated greatly from the prediction of the Fauske theory and was inconsistent with the data taken when upstream choking was absent.

The visual observations of the flow patterns during entrance choking reported in reference (7) suggest that this deviation can be attributed to the existence of metastable states during the expansion process.

These visual observations revealed that flashing of the liquid occurred almost totally in the slow moving fluid adjacent to the walls. Little visible vapor formation occurred within the core. This lack of vaporization was attributed to the high velocity of the fluid. The time of residency within the pipe of the fluid forming the core was insufficient to allow the transfers of heat and mass required for thermodynamic equilibrium. The existence of these non-equilibrium states are particularly prevalent to initial stages of bubble growth when surface tension forces tend to retard the vaporization.

In every case where upstream choking occurred in the present study, the initial bubble growth in the bulk of the fluid took place within the length of the test section. The existence of the bubble growth retardation effects mentioned above probably resulted in a lower effective vapor quality at the exit of the test section. Therefore, greater critical mass velocities were observed than suggested by the measured exit pressures.

When the initial vaporization occurred upstream of the test section, the experimental data were observed to agree well with theoretical predictions of theory. The occurrence of the later, more rapid, stages of vaporization within the test section in these cases probably resulted in a closer approach to thermodynamically equilibrium expansions.

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Figure 1. Schematic drawing of test and auxiliary apparatus.

Figure 2. Correlation of data assuming choking at exit of test section.
($E = 421 - 425$ BTU/lb)

Figure 3. Correlation of data assuming choking at exit of test section.
($E = 463 - 473$ BTU/lb)

Figure 4. Jorrelation of data assuming choking at exit of test section.
($E = 480 - 490 \text{ BTU/lb}$)

Figure 5. Correlation of data assuming choking at exit of test section.
($E = 525 - 533 \text{ BTU/lb}$)

Figure 6. Upstream axial pressure profiles in test section (E = 525 to 533 BTU/lb)

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