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HIGH FLUX HEAT TRANSFER TO SUB- AND SUPERCRITICAL WATER

Final Report

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by

P. W. McFadden

R. J. Schoenhals

January 1966

PURDUE UNIVERSITY
School of Mechanical Engineering
Lafayette, Indiana

PURDUE RESEARCH FOUNDATION
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Contract No. AT (11-1) - 1177

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ABSTRACT

This final report describes research accomplished under Atomic Energy Commission Contract No. AT (11-1) - 1177 for the period from June 1, 1962 to January 31, 1966. Results obtained during this period in five areas of investigation are briefly outlined, and appropriate references are given as a source of further detail.

INTRODUCTION

This report describes research accomplished under Atomic Energy Commission Contract No. AT (11-1) - 1177 for the period from June 1, 1962 to January 31, 1966. Before discussing this research, it is appropriate to trace its development as a logical extension of previous work. Prior to May 31, 1961 investigations associated with heat transfer to sub- and supercritical water were carried out in the School of Mechanical Engineering under the direction of Dr. Richard J. Grosh by sponsorship of the Argonne National Laboratory. This effort was continued from June 1, 1961 to May 31, 1962 under Atomic Energy Commission Contract No. AT (11-1) - 1026. Under that contract a number of these investigations were completed, and the corresponding technical reports associated with the completed phases of the research were submitted to the AEC (1, 2, 3, 4, 5, 6).¹ Contract No. AT (11-1) - 1177 was initiated on June 1, 1962 and research activities were continued until January 31, 1966. The remainder of this report constitutes a brief description of those activities. Appropriate references are given as a source of further detail.

¹ Numbers in parentheses designate References given at the end of the report.

During the contract period results were obtained and reported (7, 8, 9, 10, 11, 12, 13) for five areas of investigation. In three of these areas additional information on heat transfer to sub- and supercritical water was obtained (7, 9, 11, 13). The other two investigations were primarily oriented toward fluid flow phenomena. One of these involved natural convection flow and the onset of flow instabilities in the presence of heat transfer (8, 12). The other involved a study of acoustic velocities for fluids at high pressures and supercritical temperatures (10). The motivation for pursuing research in these two areas was derived from the increased importance of the dynamic behavior of high pressure systems under the influence of heat transfer. A description of research in each of the five areas follows this introduction.

SINGLE AND TWO PHASE HEAT TRANSFER TO
NEAR CRITICAL WATER UNDER FORCED CONVECTION
IN AN ELECTRICALLY HEATED VERTICAL TUBE

In this research an experimental investigation of forced convection heat transfer was conducted for water in turbulent flow at high pressures (7). The purpose of the study was to obtain new data on several distinct modes of heat transfer in the near critical pressure regime and to

correlate these data, either by means of existing correlation equations, or by means of relationships resulting from analysis of the experimental data.

The experimental apparatus used was a closed circuit, forced convection water loop. The test section was a vertical, electrically heated stainless steel tube approximately four feet in length with an inside diameter of 3/8 inch and a nominal wall thickness of 1/16 inch. The three modes of heat transfer studied were:

1. Single phase subcooled heat transfer with both tube wall and bulk fluid below saturation temperature;
2. Subcooled boiling heat transfer with tube wall above saturation temperature, bulk fluid below saturation temperature and no net generation of steam; and
3. Two phase nucleate boiling heat transfer with tube wall above saturation temperature and with a net generation of steam.

Experiments were conducted for pressures between 2560 and 3200 psia and for mass fluxes between 1.5×10^6 and 2.9×10^6 lb/hr ft². Bulk water temperatures ranged from 606 F to saturation temperatures, and the Reynolds number in the test section varied between 207,000 and 475,000.

Local property values, heat transfer parameters and

selected dimensionless ratios were computed for each of thirteen positions along the length of the test section. Heat transfer coefficients, based on bulk fluid temperature, were found to range from 6500 to 53,000 B/hr ft² F, and reached a peak of 107,000 B/hr ft² F at the transition point in a two phase film boiling run.

Within the range of variables covered in this investigation of boiling and non-boiling heat transfer to high pressure water in turbulent flow, the significant conclusions derived from the experimental measurements and subsequent analyses were the following:

1. All single phase subcooled heat transfer data were successfully correlated, in turn, by the well known Dittus-Boelter, Sieder-Tate, Colburn, and Prandtl equations.
2. The experimental subcooled boiling data could not be satisfactorily correlated, in turn, by the Jens-Lottes, Weatherhead, Levy, or Rohsenow subcooled boiling equations. The experimental nucleate boiling data for low qualities could not be satisfactorily correlated by the Levy boiling equation.
3. An empirical correlation equation, developed from the experimental data and based on the Prandtl equation, successfully correlated the subcooled single phase, subcooled boiling and low quality

nucleate boiling data of this investigation. The correlation equation was formed by replacing the constant in the Prandtl equation with a variable. The variable, in turn, was an experimentally determined, non-linear function of the degree of subcooling of the bulk fluid. As the degree of subcooling approached zero, the value of the variable approached 0.10.

Recommendations for additional experimental investigations included testing of the empirical correlation equation at lower pressures, higher heat fluxes, and over a wider range of Reynolds number in order to better define the validity and range of applicability of the equation. Analysis of the additional data could possibly identify further relationships which would modify or improve the empirical correlation equation.

COMBINED TURBULENT CONVECTION HEAT TRANSFER TO NEAR CRITICAL WATER

This experimental study dealt with an investigation of heat transfer to near critical water flowing through a heated vertical tube (11) in the presence of combined turbulent free and forced convection flow. Two AISI type 304 seamless stainless steel tubes of 0.245 and 0.370 inch inside

diameter served as joulean heated test sections. The range of variables covered was as follows:

Test Section Bulk Fluid Temperature	610-716 F
Pressure	3220-3400 psia
Mass Flux	$0.849-3.86 \times 10^6 \frac{\text{lb}_m}{\text{hr ft}^2}$
Heat Flux	$176,000-523,000 \frac{\text{B}}{\text{hr ft}^2}$
Wall Temperature	621-835 F
Wall to Bulk Fluid Temperature Differences	1.28-117 F

Local heat transfer and Stanton numbers were computed from the measured data. This data was checked against the Dittus-Boelter equation and good agreement was obtained for temperatures below 650 F or when the Prandtl number, based on the bulk fluid temperature, did not exceed 1.20. The more recently presented correlation of Swenson, Carver, and Kakarala was also tested. The experimental data was satisfactorily predicted by this correlation up to a temperature of 690 F. Beyond that range agreement deteriorated rapidly in the proximity of the peak temperature. The peak temperature was defined as the temperature at which the isobaric specific heat curve peaked and achieved its maximum value.

The effect upon heat transfer of the proximity of both the wall and/or fluid temperatures to the peak temperature was tested. However, the range of the equipment did not allow testing with the bulk fluid temperature above the

peak temperature. Very large heat transfer coefficients were obtained for conditions where the wall and/or fluid temperatures approached the peak temperature. The data was presented in the form of the Stanton number modified to remove the difficulty with the specific heat term.

Fluctuations were detected in the pressure drop across the test section. These perturbations were present during all isothermal and heating operations at all temperature and pressure levels. The amplitude of the fluctuations magnified at the near critical operations. The cause and the effect of the vibrations could not be determined accurately.

Consideration of the experimental observations and the results led to the following conclusions:

1. Large heat transfer coefficients can be expected for heat transfer to critical water in turbulent upward flow through tubes. Very large heat transfer coefficients were obtained at small wall-to-bulk fluid temperature differences; however, uncertainty in the computation of the inside wall temperature caused considerable difficulty in determining these values accurately.
2. The Dittus-Boelter equation was proved to be inadequate for use with water at temperatures above 650 F, or when the Prandtl number, based on the

bulk fluid temperature, exceeded 1.20. The upper limit beyond which the equation may again be found useful could not be determined from the results of this investigation.

3. The recent correlation of Swenson et al. proved adequate up to around 690 F in general. It showed progressive deviation for temperatures closer to the peak temperature.
4. For applications up to 650 F the Dittus-Boelter equation would be preferred.
5. The failure of equations of the Dittus-Boelter type in the near critical region is associated with their inadequacy to respond to large variations in the Prandtl number. In this region the Nusselt number is more strongly dependent on the properties, which undergo large changes, than on the Reynolds number alone.
6. The use of Stanton number, St_e , appears to be quite promising. However, more extensive data must be obtained in order to arrive at a firm conclusion. Reduced enthalpy appears to be a good parameter to use for purposes of correlations associated with the near critical region.
7. A correlation of the type

$$St_e Re^a = c e^{b(H_b/H_p)}$$

is recommended for use in conjunction with near critical water. In this formulation Re is the Reynolds number, H_b and H_p are the bulk and peak enthalpy values, and a , b , and c are constants.

TURBULENT FREE CONVECTION IN NEAR CRITICAL WATER

This research involved an analytical and experimental study of heat transfer from a vertical flat plate by turbulent free convection to single-phase water near its thermodynamic critical point (9, 13). In this work there were three major objectives. The first one was to establish an analytical model and method for the prediction of heat transfer in this region, the second was to experimentally measure actual heat transfer data supporting the analytical work, and the third was to provide a simple method of presentation of the results in a form convenient for design purposes.

An analytical method was developed to predict the magnitudes and trends associated with the heat transfer coefficient in this region. This method involved an integral technique as well as assumptions of Reynolds analogy, the Blasius wall shear stress, and suitable velocity and temperature profiles. The energy equation was written in terms of enthalpy in order to avoid certain difficulties

associated with the highly variable properties in the critical region. Because of the complexity of expressions required to describe the variations of some of the properties with temperature, numerical integration was employed in order to obtain predicted values of the heat transfer coefficient.

Experimental measurements were made using a heated platinum ribbon suspended in a pressure vessel containing the test water. The ribbon was heated electrically by direct current. During operation of the system voltage measurements were made at several points along the length of the ribbon in order to determine local heat generation rates and local temperatures. The ribbon temperatures were determined by using the experimentally determined resistance values together with a previously obtained calibration consisting of the resistance-temperature curve for the test section. From these measurements, values of the local heat transfer coefficient were obtained. The temperature of the bulk fluid was determined by use of a platinum resistance thermometer. The measurements were reproduceable and the plotted experimental values of the heat transfer coefficient exhibited very little scatter.

The experimental results were compared to the analytical predictions, and similar trends and magnitudes were found. However, deviations between the predicted and measured values were considerably larger than the uncertainties

associated with the measurements. This illustrated the strong limitations of the analytical method used. Some 77 data points for both 3240 and 3300 psia, representing various temperatures and temperature differences, were used to develop a correlation which gave reasonable predictions of the data in terms of the usual dimensionless parameters. The average deviation of the experimental values from the results given by this relation was about 15 percent.

The general agreement between the experimental data and the relatively simple model provides further evidence that heat transfer in the near critical region may be adequately described by conventional methods by taking into consideration the property changes which occur. No unusual trend or phenomenon was observed which would indicate another mechanism by which heat is transferred in the near vicinity of the thermodynamic critical point.

FREE CONVECTION FLOW IN CIRCULATION LOOPS

In this investigation single-phase natural circulation flow in a circular loop was studied both analytically and experimentally (8, 12). The analytical results for both laminar and turbulent flows were obtained in a straightforward manner and were presented graphically in dimensionless form. The application of these graphical results to a

particular situation was shown to require an iterative procedure in general due to the nature of the dimensionless parameters involved. The iterative procedure was programmed so that the details could be carried out using digital computer calculations for the system used in the experimental portion of the investigation. It was found that in some instances the analytically obtained graphical information can be used in conjunction with manual iterative calculations to produce reasonably good predictions. However, the computer program provided the advantage of carrying out large numbers of iterative calculations rapidly, thus avoiding excessive hand calculations. The manual calculations were found to produce poor accuracy for some operating ranges, a difficulty that was easily rectified by using the more accurate computer calculations. The lesser accuracy of the manual method in these regions is due to the fact that numerical values cannot be obtained precisely enough by visual inspection of the curves representing the generalized dimensionless correlations.

The computer program was capable of accounting for fluid property variations as well as providing a means for using improved correlations to obtain values of the convection coefficient over the top portion of the loop. Despite these advantages, the program was limited by the fact that there was no convenient alternative to using the standard forced convection correlations for calculating values of the

convection coefficient. This procedure really amounted to an assumption which was found to be reasonable, based on the experimental observations, except for the higher input heat fluxes used.

An experimental apparatus was used to obtain measurements for comparison with the computer-calculated predictions. The qualitative agreement was found to be favorable with respect to general trends and order of magnitude of the numerical results obtained. Both predicted and measured results illustrated increases of circulating fluid temperatures and flow rates with increasing input heat flux.

Moderate deviations of the analytical results from the corresponding experimentally obtained values were found. Predicted flow rates in the laminar range were somewhat larger than observed, the difference probably being due to the simplicity of the analytical model. In particular, the model did not account for a reduction in the actual buoyant torque produced by variations in the local convection coefficient. For the largest rates of input heat transfer used, where the flow was definitely turbulent, the correlation used to calculate the convection coefficient produced values considerably larger than those observed experimentally. This caused the fluid temperature predictions to be lower than the measured values. Predicted flow rates in this region were somewhat lower than observed, most probably due

to fluid property variations occurring over the range of the temperature deviations.

Following the completion of the analytical and experimental research on steady flow characteristics of circular loops, an investigation of the stability of these flows was undertaken. A review of the literature revealed that observations of oscillatory unstable behavior of such flows are fairly common, but that sufficiently detailed explanations of the mechanisms by which these instabilities occur are rather sparse. Harden (14) succeeded in identifying two separate modes of unstable oscillatory behavior for a loop operating under single-phase conditions near the fluid critical state; one, occurring at relatively high frequencies which was attributed to sonic effects resulting from the compressibility of the fluid, and a second low frequency mode of oscillatory instability which was stated to be associated with enthalpy transport. By using a digital computer Harden was able to simulate the experimental loop used by means of finite difference equations as other investigators have done, and the computer output exhibited the low frequency instabilities in agreement with the behavior observed for the experimental system.

The above example is typical of the extent to which the loop instability phenomena has been studied. Some trends have been established and a certain amount of insight has been achieved. However, regions of stable and unstable

operation in terms of limiting values of various system parameters are not generally available from the literature. In the investigation reported on here, an analytical perturbation method was developed which yielded the stability threshold conditions for the circular loops studied. These threshold conditions represent the division between stable and unstable regions of operation. The calculations were carried out and the results, in terms of three dimensionless parameters, were plotted. The experimental verification of these stability predictions has not yet been attempted, although future research efforts in that direction are planned.

ACOUSTIC VELOCITIES FOR HIGH PRESSURE CARBON DIOXIDE AND WATER AT SUPERCRITICAL TEMPERATURES

In this investigation calculated values of the acoustic velocity were obtained for high pressure carbon dioxide and water at supercritical temperatures (10). Systems utilizing fluids at high pressures and temperatures have become more common in recent years, and the dynamic behavior and stability characteristics of these systems have been associated with a number of challenging engineering problems (11, 12, 14). In certain situations the velocity of pressure waves traveling through the fluid is of considerable importance in influencing the dynamic behavior of the system. Thus,

the acoustic velocities of fluids contained in these devices are of interest.

In the investigation reported here, carbon dioxide was studied initially because of the availability of published experimental data for comparison purposes. Calculated values for carbon dioxide varied depending upon the equation of state that was used in carrying out the calculations. However, all of the predicted results exhibited distinct decreases in the acoustic velocity in the immediate vicinity of the critical point. Because of its technical importance, calculations were also carried out for water using an improved equation of state. For water the minimum acoustic velocity values were obtained in the region of the critical point in agreement with the trends found in the results for carbon dioxide. The lack of sufficient experimental data for water prevented an adequate comparison of predicted and experimental results.

The analysis used was based solely upon thermodynamic principles. The resulting expression for acoustic velocity turned out to be a function only of specific heat and quantities which could be determined directly from the equation of state of the fluid. The calculated values for carbon dioxide and water, when plotted at constant temperature, showed the same trends as those exhibited by the available experimental carbon dioxide data. The plotted results illustrated a significant drop in the acoustic

velocity values in the critical region. The accuracy with which the calculated velocities for carbon dioxide agreed with the available experimental data varied depending upon which equation of state was used. For both water and carbon dioxide the curves showing the variation of acoustic velocity with specific volume at constant temperature failed to yield the sharp, cusp-like appearance exhibited by the experimental curves in the critical region. The accuracy of the prediction near the critical point for water could not be adequately demonstrated because of the lack of sufficient experimental data.

It is clear that experimental data is needed to verify the magnitudes of the acoustic velocities, as well as the general trends, in the critical region for water. To improve the accuracy of the analysis and to determine whether the thermodynamic approach is adequate very near the critical point, a highly accurate equation of state and more reliable information on specific heat are needed. In order to eventually develop an adequate theory for accurately predicting acoustic velocities in the critical region, properly accounting for frequency effects, a better understanding of the physical nature of near critical fluids must be achieved.

SUMMARY

Research under Atomic Energy Commission Contract No. AT (11-1)-1177 was conducted from June 1, 1962 to January 31, 1966. The five areas investigated were:

1. Single and Two Phase Heat Transfer to Near Critical Water Under Forced Convection in an Electrically Heated Vertical Tube
2. Combined Turbulent Convection Heat Transfer to Near Critical Water
3. Turbulent Free Convection in Near Critical Water
4. Free Convection Flow in Circulation Loops
5. Acoustic Velocities for High Pressure Carbon

Dioxide and Water at Supercritical Temperatures

For the first three areas listed above additional information on heat transfer to sub- and supercritical water was obtained.

For the last two areas listed results were obtained which relate to fluid flow, flow instabilities, and the dynamic behavior of fluids at high pressures and temperatures.

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