The Effect of Applied Voltage on Boiling Heat Transfer

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The effects of electrostatic fields on the motion of particles and fluids have received considerable attention since 1958, when Pohl (*11*) described several phenomena occurring in dielectric liquids as the result of impressed fields. In boiling heat transfer impressed fields caused destabilization of film boiling and increased heat transfer coefficients, as reported by Bochirol, Bonjour, and Weil (*3*) in 1960. The geometry in their experiments consisted of a pair of parallel wires, one heated electrically, with a secondary a.c. voltage impressed between them. The boiling fluids were dielectric in nature, and the increase in heat flux was attributed to dielectrophoresis* by Bonjour and Verdier (*4, 5*). Large increases in natural convection heat transfer from wires were also reported by Bonjour and his co-workers.

The results of Bonjour, et al. were recently corroborated by Choi (*7*), who employed a cylindrical geometry and direct current voltage to study boiling of dielectric liquids on these wires. Much of the heat transfer increase observed in the tests with wires appears to be caused by increased mixing which may be attributed to dielectrophoresis, especially under natural convection conditions.

The phenomena of large increases in boiling heat transfer and prevention of film boiling in nonuniform electrical fields may prove to be of great practical value in such applications as nuclear reactors and evaporator sytems. The work reported herein was performed to ascertain effects of voltage during boiling on a steam-heated tube, as opposed to an electrically heated wire used by previous investigators. In addition to providing a heating surface somewhat more representative of industrial equipment the steam-heated tube allowed investigation of surface temperatures normally associated with transition and film boiling regions.

APPARATUS

A simple pool-boiling apparatus designed to allow close visual observation was constructed for evaluating effects of applied voltage on the pool boiling process. A horizontal ⅜-in. chromeplated copper tube was heated by saturated steam promoted by oleic acid and blown through the system. For these conditions a steam side coefficient of up to 20,000 B.t.u./hr.-sq. ft.-°F. can be estimated based on published data (*10*). While this high a steam side coefficient may not have been maintained in every run, a negligible temperature drop on the steam side was assured by the high steam velocity. The overall temperature differences reported in this work may therefore be taken to represent ($T_s - T_{sat}$), the boiling side driving force.

The steam tube was insulated from a rectangular, glass-fronted aluminum tank by teflon spacers. The boiling surface between the spacers was 3 in. long.

The boiling liquid was isopropyl alcohol, chosen because all three regimes of boiling could be studied with the steam pressure available and also because of the availability of physical data on isopropanol. The electrical resistivity of the alcohol used was 1.9×10^6 ohm-cm. at the boiling point, except when ammonium perchlorate was added in specific runs. The electrical resistivity of the alcohol vapor was essentially infinite over the voltage range used. Distilled water was also used in some tests.

Direct or alternating current voltage was applied between the aluminum tank (high voltage) and the steam line (ground). Readings of both voltage and amperage were taken. The alcohol in the tank was maintained at its boiling point by electrical heating strips on the glass front of the tank, and the liquid temperature was measured with a total immersion thermometer. The alcohol vaporized by the boiling process was condensed and fed back into the tank. The flow rate of condensed alcohol was measured by a rotameter. During preliminary tests a heat balance was obtained by trapping and collecting the condensed steam. The heat supplied by the condensed steam checked within 2% of the heat calculated from the condensed alcohol flow, so no further measurements of steam condensate were taken.

EXPERIMENTAL MEASUREMENTS

The procedure used in operating the apparatus consisted of taking rotameter readings at constant steam pressure for various impressed voltages. There was no discernible difference between rotameter readings with increasing steam pressures and readings with decreasing steam pressures. The condenser was open to the atmosphere so that the boiling occurred at a pressure very close to ambient.

The ranges of variables tested with isopropanol were as follows: heat flux 0 to 9×10^5 B.t.u./hr.-sq. ft., overall temperature difference 40° to 260°F., current 0 to 20.1 mamp., overall impressed voltage 0 to 10,000 v. Both direct and alternating current were used. Qualitative testing was also performed with other geometries and with distilled water.

CALCULATIONS

The primary calculations were straightforward and consisted of the following. Heat flux was calculated from the rotameter readings. The overall temperature difference was calculated from the boiling point of the isopropyl alcohol and the steam pressure.

Two other measured quantities were the total impressed voltage and the current. The authors postulate that the electrical resistance of the bulk liquid alcohol remained constant irrespective of the heat transfer. On this basis the voltage drop in the liquid can be calculated as can the voltage drop across the vapor formation zone. The relative resistance of the vapor formation zone can be taken as a measure of the relative wetted area of the heat transfer surface. While the analogy is not exact, it is useful in relating the current and voltage readings to the heat transfer process.

In the determination of relative wetted area for boiling isopropanol the electrical resistance through the region of vapor formation was assumed inversely proportional to the contact area, giving

$$\frac{R_{nb}}{R_b} = \frac{A_w}{A} \tag{1}$$

The relative wetted area during the application of high voltage was calculated by the use of Equation (1) in the following manner:

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* Dielectrophoresis denotes motion of a dielectric fluid placed in a nonuniform electrical field, caused by induced polarization. In a boiling situation the liquid tends to move toward the region of greatest field strength.

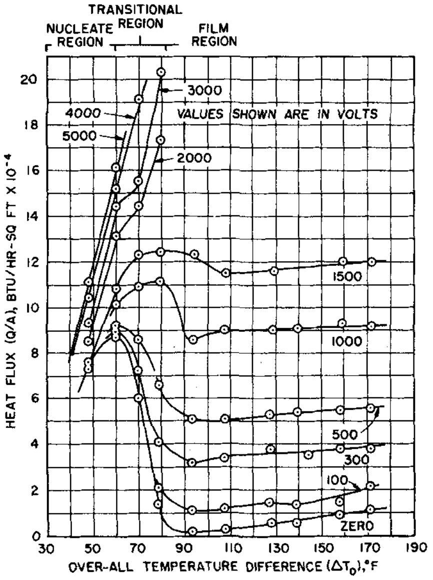

Fig. 1. Effect of d.c. voltage on pool-boiling heat transfer (isopropanol at 1 atm.).

1. R_{nb} was measured between the steam tube and a probe near the tube. Six measurements were taken at low voltage, the average of which was 0.40×10^6 ohms.

2. At no boiling and with the voltage applied the total resistance without boiling, R_a, was calculated by Ohm's law from the impressed voltage and the current.

3. With boiling and with the voltage applied the total resistance with boiling, R_t, was calculated by Ohm's law.

4. R_b, the resistance across the region of vapor formation during boiling, was then calculated by

$$R_b = R_t - R_a \tag{2}$$

5. A_w/A was then calculated by

$$A_w/A = \frac{0.4 \times 10^6}{R_b} \tag{3}$$

The measurements mentioned above with no boiling were taken with the isopropyl alcohol at its boiling point.

For the zero voltage case a similar approach was used except that the alcohol was made conductive with ammonium perchlorate in order to bring the resistance readings to a convenient range for measurement with a Wheatstone bridge at a total voltage of less than 1 v. Although the ammonium perchlorate (0.13 molar) increased the boiling point about ½°F., there was very little apparent change in the shape of the heat flux curve.

RESULTS AND DISCUSSIONS

Preliminary heat flux and ΔT_o measurements at zero voltage were made for comparison with published values. The maximum in the Q/A vs. ΔT curve for isopropanol occurred at a ΔT_o of 60°F., corresponding to a measured Q/A of 87,000 B.t.u./hr.-sq.ft. and a heat transfer coefficient of 1,450 B.t.u./hr.-sq.ft.-°F. These values compare quite well with the measurements reported by Kaulakis and Sherman (*9*) of a maximum coefficient of about 1,500 B.t.u./hr.-sq.ft.-°F. at a ΔT of 60°F. for pool boiling isopropanol on a chrome-plated copper tube. For isopropanol boiling on an uncoated copper tube Dunskus and Westwater (*8*) measured a peak Q/A of 90,000 B.t.u./hr.-sq.ft. at a ΔT of 40° to 50°F. The peak heat flux and the corresponding temperature difference were found to vary somewhat with the purity of the alcohol and with the surface condition. Similar variations have been observed by many investigators (*8*, *12*).

The effects of applied voltage on the heat flux vs. overall temperature difference curve is shown on Figure 1. At low voltage only the normal film-boiling region was affected, while at the higher voltages the peak heat flux was increased and the corresponding temperature difference shifted until the maximum was no longer observed for the test conditions used. Above 500 v. only nucleate boiling was observed, whereas at and below 500 v. the boiling appeared transitional in nature.

The data shown on Figure 1 was taken with d.c. voltage with the aluminum tank charged positively and the heating tube at ground potential. Reversing the polarity did not affect the heat transfer rate at a given voltage. The power consumption at the heat fluxes plotted on Figure 1 ranged from 0.0068 w. at 100 v. to 1.95 w. at 1,500 v. in the normal film-boiling region. The power consumption in this region was constant for each voltage. At 3,000 v. for a ΔT_o of 79°F. the electrical power used was 8.1 w. at a total heat transfer rate of 1,930 w. and an increase in heat transfer over film boiling of about 1,830 w. This represents an amplification factor of 226, which is seldom found in heat transfer phenomena. The electrical power dissipation includes both the power dissipated in the region of vapor formation and the power dissipated in the bulk alcohol. Typically the electric power dissipated in these two regions were roughly equal in the geometry of the authors' tests.

Tests made with alcohol at higher voltages and temperature differences than those reported on Figure 1 were made to determine whether the heat flux would continue to increase as both ΔT_o and voltage increased. These results are shown on Figure 2. The maxima and minima corresponding to those for the zero voltage case appear, from Figure 2, to be characteristic of the boiling phenomenon, although the values of Q/A and the corresponding temperature differences at high voltage are much different from those for zero voltage. The plot at 10 kv. could not be extended to the maximum because of equipment limitations. The data on Figure 2 strongly indicates that the boiling heat flux obtainable from the application of voltage is limited by neither surface temperature nor voltage, provided that a suitable liquid is used.

When a second unheated copper tube of identical area was introduced into the tank and connected electrically to the heated tube, the increase in heat flux over normal film boiling by impressing 500 v. d.c. between the tank and the grounded tubes was reduced to 80 to 90% of the

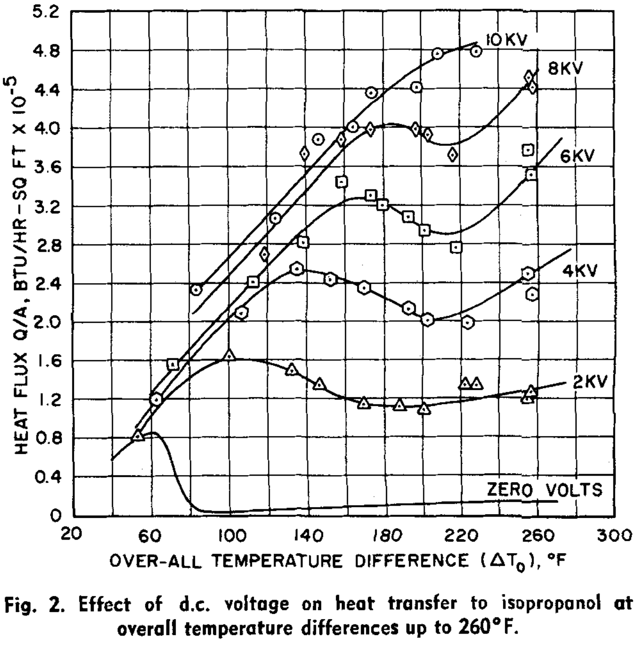

Fig. 2. Effect of d.c. voltage on heat transfer to isopropanol at overall temperature differences up to 260°F.

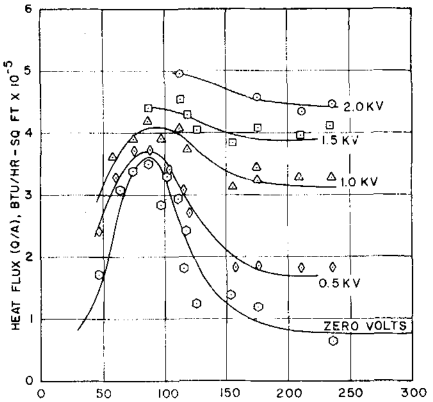

Fig. 3. Effect of applied a.c. voltage on boiling heat transfer to distilled water (resistivity 1.2 to 1.8 × 10^5 ohm-cm. at 20°C.).

increase at the same voltage with the single tube present. However the current was increased from 3 ma. to 12 ma. This test showed that film boiling on one portion of a heat transfer surface can be destabilized electrically even if there is no boiling taking place elsewhere.

Alternating current voltage was also used in another test series with alcohol. Comparison of heat flux measurements at equal values of d.c. and a.c. (root mean square) voltage (negligible phase angle for 60 cycle a.c.) showed that the heat flux with d.c. was 10 to 50% higher than with a.c. and that the d.c. dissipated approximately one-third the power required to maintain the a.c. voltage.

Frequency traverses from 50 to 5,000 cycles/sec. were made with a.c. current at various voltages. No resonance frequencies were observed, and there was very little variation of heat flux with frequency in the range covered. At the lowest and highest frequencies the heat flux tended to decrease slightly.

Results similar to those shown on Figure 1 for alcohol were obtained for distilled water and are presented on Figure 3. Owing to electrolysis difficulties with d.c., 60 cycle alternating current was used. The a.c. voltage which could be applied was limited by sparking between the liquid and the heated tube. Sparking occurred at about 2,500 v. and resulted in a current increase exceeding the limits of the transformer protection. The resistivity of the water was about 1.5 × 10^5 ohm-cm. It has been found in later work that the observed sparking can be eliminated by the use of more resistive water.

Photographs of the boiling process with and without applied voltage are shown on Figures 4, 5, and 6. Figure 4 shows normal nucleate boiling, while Figures 6 and 5 show boiling in the normal film region with and without applied voltage, respectively. The boiling with a fully destabilized vapor film closely resembled normal nucleate boiling, except that with the voltage applied more vapor was visible between the tube and the surface of the liquid, and the individual bubbles forming on the heat transfer surface appeared slightly smaller than with no voltage.

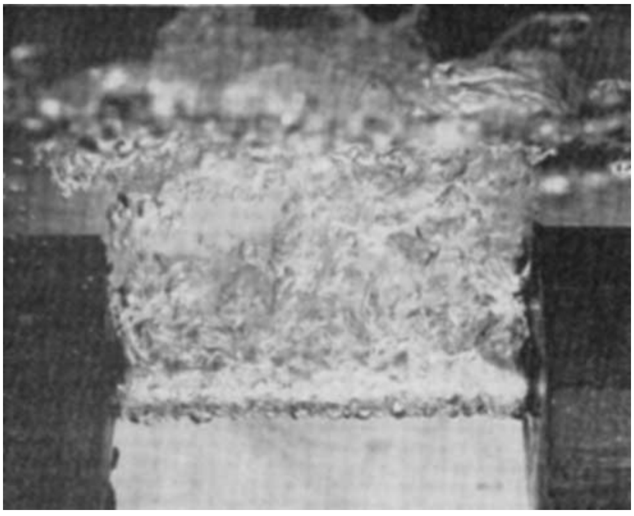

Fig. 4. Normal nucleate boiling of isopropanol $\Delta T_o = 60$°F.

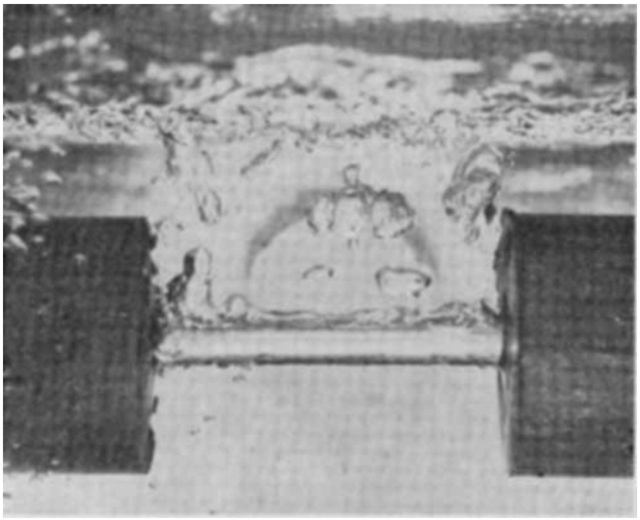

Fig. 5. Normal film boiling of isopropanol $\Delta T_o = 115$°F.

The photographs of the boiling process (Figures 5 and 6) indicate that a sufficiently high voltage applied during normal film boiling caused wetting of the heat transfer surface, resulting in nucleate boiling. The degree of surface wetting, as estimated by the current and voltage readings, appeared to be an attractive tool in the analysis. A plot of the relative wetted area (A_w/A) vs. overall temperature difference for isopropanol is shown on Figure 7. The data for zero volts were taken with the alcohol made conductive with 0.13 molar ammonium perchlorate. The measured value of A_w/A of 0.65 for peak nucleate boiling appears reasonable when compared with the value of 0.5 for the critical packing fraction at peak nucleate boiling given by Bankoff (*1*). Note that the value of A_w/A appears to be above 0.50 for most of the transition region, indicating a large degree of surface wetting for transitional boiling up to the onset of film boiling. These results substantiate the theory extended by Bankoff (2)

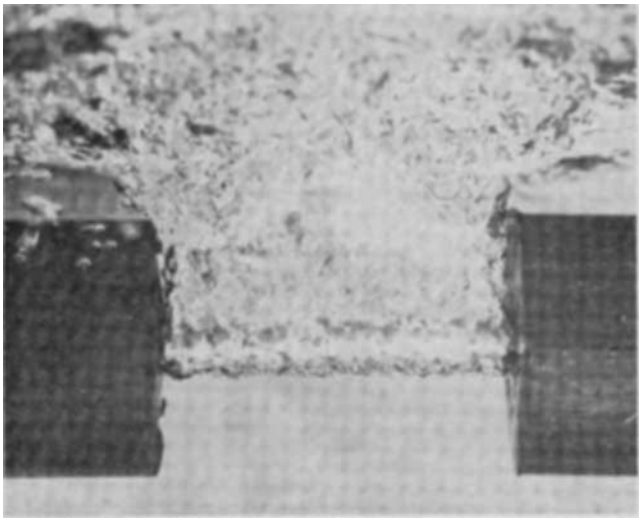

Fig. 6. Electrostatic effect, film fully broken by 1,000-v. d.c. for isopropanol ($\Delta T_o = 87$°F.).

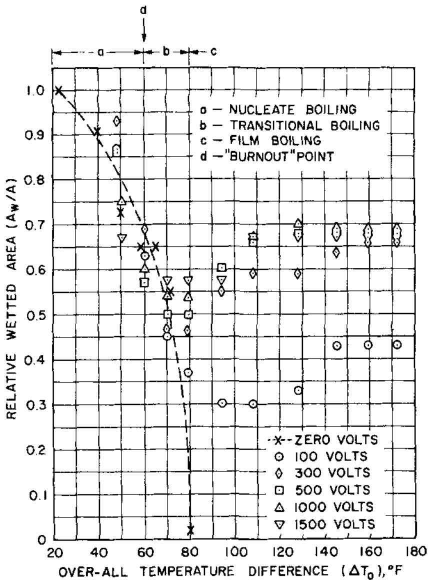

Fig. 7. Variation of relative wetted area (A_w/A) with ΔT_o at various applied voltages (pool-boiling isopropanol).

that the heat transfer surface is wetted during transitional boiling.

In order to compare the values of A_w/A at zero voltage with A_w/A with voltage, the measured voltages and currents were used to calculate A_w/A by Ohm's law and Equation (3). The results of these calculations are also shown on Figure 7. The plots on Figure 7 closely resemble the plots of Q/A vs. ΔT_o on Figure 1 in shape. This similarity indicates a strong effect of wetted area on the heat flux, and therefore an important effect of the applied voltage was to bring the liquid phase into contact with the heated tube.

On Figure 7 as the voltage increased the value of A_w/A in the ΔT_o range 120° to 180°F. increased until the voltage reached 1,500 v. At 1,500 v. the magnitude of A_w/A in the flat part of the curve was decreased slightly, even though the heat flux continued to increase. This can be explained by a change in the shape of the bubbles in the electrostatic field resulting in smaller bubbles and/or a larger wetting angle. Comparison of photographs of nucleate boiling and fully destabilized film boiling (Figures 4 and 6) indicated that the bubbles under the influence of voltage were indeed smaller than in normal nucleate boiling.

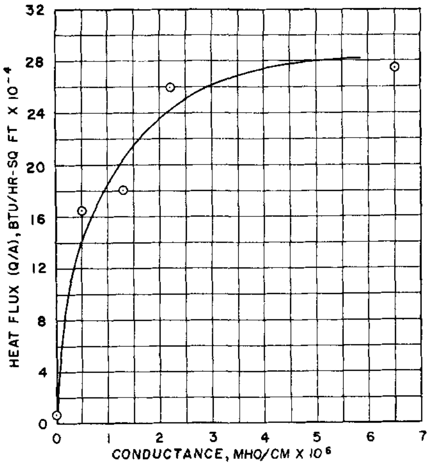

Fig. 8. Effect of electrical conductance on boiling heat transfer with impressed voltage of 3-kv. d.c. and of 145°F. (pool-boiling isopropanol at 1 atm.).

One series of runs was made in which the electrical conductivity of the alcohol was increased by incremental additions of ammonium perchlorate, and the heat transfer rates were measured at a constant applied voltage of 3,000 v., d.c. The data from this experiment are presented in Figure 8. Since the heat flux increased as the voltage drop through the alcohol decreased (and therefore as the voltage drop across the region of vapor formation increased), it may be concluded that the driving force of the observed voltage effect was the voltage drop across the region of vapor formation.

At least two general effects of an electrical field on heat transfer from a surface to a liquid are possible:

1. Dielectrophoresis (or the action of a nonuniform field on an induced dipole within the field).
2. Condenser effect (or the coulomb attraction between the charged surfaces of a dielectric or the plates of a condenser).

Mathematical expressions for these two effects show that the former depends on the gradient of the field strength squared and the dielectric constant, while the latter depends only on the value of the field strength squared. A discussion of the mathematics involved can be found in a review prepared by Velkoff (*13*).

No attempt was made in this work to differentiate between the two possible electrical effects or to quantitatively determine the relative importance of each. It appears likely however that differences exist between voltage effects when a relatively large diameter heat tranfser surface is used and when the boiling takes place on a thin wire. The basis of this statement is that voltage drops of a few kilovolts per centimeter through the liquid in the work with tubes produced substantially the same effects reported by Bonjour, et al. (*6*) from voltage drops from 50 to 150 kv./cm. with wires.

While the approach in this investigation has been exploratory, one comment of some immediate practical interest might be made. Nuclear reactor heat transfer experiments are typically made with electrical resistance heating to simulate the fission heat. This is done with the implied assumption that all of the conditions which are not simulated accurately, such as radiation flux, will increase the heat transfer in the reactor or reduce the heat transfer in the electrical simulator. The applied voltage effect is the first effect which may cause the simulating experiment to show better heat transfer than the reactor, giving results which are not conservative. This can be avoided by grounding the electrical heater to the rest of the loop piping at the burnout point rather than grounding at the inlet or some other point in the electrical system.

CONCLUSIONS

1. A large increase in boiling heat transfer to isopropyl alcohol from a steam-heated tube was observed under the influence of d.c. voltage. The vapor film during film boiling was partially destabilized by d.c. voltage up to 500 v. and was completely destabilized by voltages of 1,000 v. or more, resulting in transitional boiling at the lower voltages and in nucleate boiling at the higher voltages. The same effect was noted with boiling distilled water with 60 cycle a.c. voltage used.
2. Relative wetted area measurements indicate increased surface wetting in the normal transitional and film-boiling regions when voltage was applied. The driving force for the surface wetting appears to be the voltage drop across the region of vapor formation operating through condenser and dielectrophoretic forces.

ACKNOWLEDGMENT

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NOTATION

A = heat transfer area, sq. ft.
A_w = wetted area, sq. ft.
Q = heat transfer rate, B.t.u./hr.
R_a = total resistance without boiling, ohms
R_b = resistance across the region of vapor formation with boiling, ohms
R_{nb} = resistance across the region of vapor formation with no boiling, ohms
R_t = total resistance with boiling, ohms
T = temperature, °F.
ΔT = temperature difference (wall minus saturation), °F.
ΔT_o = overall temperature difference (Steam temperature-alcohol boiling point), °F.

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Simplification of the Mathematical Description of Boundary and Initial Value Problems

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Methods of reducing the number of parameters and independent variables in a mathematical model have been investigated for many years. Investigations of the parametric description of a problem are carried out under such terminology as dimensional analysis, modeling, scale-up laws, and inspectional analysis. Methods of reducing the number of independent variables are usually considered separately. The method of similarity transformations is discussed by Schlichting (*1*). In this well-known method the transformations of variable are assumed to be of a certain general form and are then defined specifically by direct introduction into the original system of equations. Birkhoff (*2*) describes a different approach based on group theory. In this latter method, called *the method of search for symmetric solutions,* a group of transformations is found under which the differential equations and conditions are invariant. Then a solution is sought which is invariant under the same transformation.

The fundamental simplicity and power of the method of search for symmetric solutions are well known, at least among workers in group theory. However there are two important extensions of this method which do not seem to have been noted or generally appreciated.

One extension is that the problem of finding the minimum parametric description can be directly related to the problem of finding the minimum description in terms of independent variables. In fact any systematic method of inspectional or dimensional analysis which leads to the minimum number of parameters can also be shown to lead directly to similarity transformations in many cases. This consequence makes it possible to find the minimum description of a problem in terms of both variables and parameters by use of a single, direct method. This new direct method is the subject of this paper. The new method is easily shown to be equivalent to the two separate procedures used by Birkhoff: "inspectional analysis" and "search for symmetric solutions."

The second extension is the use of the method of search for symmetric solutions and hence the method described in this paper for problems involving arbitrary functions. The new method may thus be applied to yield the classes of functions which admit the possibility of a similarity transformation. Needless to say a reduction in the number of independent variables constitutes an important simplification whether the reduced problem is to be solved analytically, numerically, or experimentally. Application of the method to arbitrary functions is particularly useful in that the effect of idealizations may be examined in detail. In many cases it is possible to find similar solutions, approximate solutions, or solutions of asymptotic validity.

The method will be illustrated below for several problems of general interest. A simplified form of the method has been discussed in an earlier paper on natural convection (*3*) in which only cases of fixed mathematical description were considered. In the more general method