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BUBBLE FORMATION AND GROWTH

Study of the Boundary Conditions at a Liquid-Vapor Interface through Irreversible Thermodynamics

by

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ABSTRACT

During the last three months attention was focused mainly on the experimental part of this program. An experimental apparatus was designed to measure the previously defined transport coefficient by means of the steady state evaporation experiment. All of the necessary equipment has been ordered, some of the system has been assembled, and calibrations are underway.

NOMENCLATURE

h	specific enthalpy
h_{fg}	latent heat of condensation or evaporation
J_i	mass flux
J_u	energy flux
K	transport coefficient
L_{ii}	transport coefficient
L_k	transport coefficient
P	pressure
p_g	system pressure
R	gas constant
T	temperature
α	energy accommodation coefficient
γ	specific heat ratio, c_p/c_v
s.s.	denotes steady state
g	denotes vapor

I. INTRODUCTION

In past reports the no-flow experiment was discussed in detail and mention was made of the problems expected in such an experiment.[1] It was decided that a more feasible method for determining the transport coefficients involves carrying out a steady-state evaporation experiment. This experiment and the apparatus to be used is discussed in this report.

II. STEADY-STATE EVAPORATION EXPERIMENT

A steady-state evaporation experiment, as is illustrated in Figure 1, is one in which liquid changes to the vapor phase at a constant rate by evaporation at the liquid-vapor interface with the absence of boiling and in which the heat transfer necessary for evaporation is all from the liquid side of the interface. There is no heat transfer to the vapor. For such a case the first law requires that the temperature in the bulk flow region of the vapor be uniform and therefore that

$$(J_u)_{s.s.} = h_g (J_i)_{s.s.} \tag{1}$$

In such a case the energy equation of the phase change[2] becomes

$$\frac{K}{K+1} = -\frac{L_k (\delta T)_{s.s.}}{h_{fg} (J_i)_{s.s.} T^2} \quad , \tag{2}$$

and the mass flux equation[3] becomes

$$\left(\frac{\delta P}{\delta T}\right)_{s.s.} = \frac{P}{RT^2}\left[\frac{K}{K+1} h_{fg} + \frac{K+1}{K} \frac{L_k}{L_{ii}} h_{fg}\right] \quad . \tag{3}$$

Thus from the measured quantities T_g, δT, P_g, and J_i, one could determine K and L_{ii} from equations (2) and (3) if L_k were known. An expression for L_k has been found by employing Kennard's[4] temperature jump analysis

$$L_k = \left(\frac{\gamma + 1}{\gamma - 1}\right) \sqrt{\frac{R}{2\pi}}\, T^{3/2}\, P\left(\frac{\alpha}{2 - \alpha}\right) \tag{4}$$

where γ is the ratio of specific heats and $\alpha \approx 1$[5] is the energy accommodation coefficient.

Calculations showed that the fluids for which the desired results could be most readily measured were the liquid metals. Of these mercury is the easiest to use, and it was thus chosen as the working fluid.

III. EXPERIMENTAL APPARATUS

A flow diagram of the experiment is sketched in Figure 2. A thin layer of liquid mercury on the nickel block will be evaporated, the necessary heat being supplied by heaters placed in the nickel. The temperature distribution in the nickel block will be measured with thermocouples and extrapolated through the liquid layer to determine the temperature on the liquid side of the interface T_{fi}. To extrapolate it is necessary to know the depth of the liquid layer. The liquid depth will be determined by measuring the displacement of a probe when it is moved from the solid nickel surface to the liquid surface by means of micrometer heads.

Nickel was chosen as the material for the heating block because mercury wets nickel. It does this by forming an amalgam on the nickel surface. It is necessary to have a wettable surface if a thin film of liquid is to be realized; also the wetting eliminates any contact resistance which may exist at the solid-liquid interface.

Laplace's equation was solved for the temperature field in a two-dimensional heater block. The effect of the non-uniform temperature due to the heaters at the bottom of the block and side-heat losses were included in the boundary conditions. It was found that the thermocouples will lie in a constant temperature region of the block for about 10 probe diameters, thus eliminating the problem of conduction along the thermocouple leads.

It is desirable to have a thin layer of liquid because then any error in the extrapolation which may exist due to a non-linear temperature profile in the liquid, because of convection, will be minimized. Also a thin layer of liquid will minimize the possibility of having active nucleation sites for boiling.

The depth of the liquid layer will be controlled by adjusting the slope of the nickel block, the height of the weir placed at the downstream end of the nickel block, and the flow rate.

It should be noted that there is a means of having a liquid flow rate into the test section which is greater than that evaporated. This excess flow rate is termed the overflow. The reason for incorporating the overflow is to provide some means of keeping the liquid surface clean.

The temperature in the vapor T_{gi}, which must be uniform to satisfy the first law requirements for steady state evaporation, shall be measured by thermocouples at various points.

The thermocouples are copper-constantan enclosed in stainless steel sheaths. They will be calibrated against a standard platinum resistance thermometer.

The rate of evaporation, J_i, will be determined from the heat transfer to the liquid, which is given by the temperature gradient and conductivity in the nickel and the latent heat h_{fg}. A means of checking the above flow rate measurement is to take the difference between the liquid flow rate into the test section and the overflow rate.

The pressure in the test section P_g will be measured by a monometer. One leg of the mometer will be connected to a plenum chamber which is in turn kept at zero pressure by a vacuum pump. The other leg of the mometer will be connected to the test section. Since room temperature is less than the saturation temperature in the test section, any mercury vapor in the monometer lines would tend to condense. Eventually condensate would form in the monometer. To eliminate this the monometer line will be flushed out with argon prior to a test run, and so the mercury vapor will have to diffuse through the argon before it gets to the monometer. The line will also be placed at an angle to the horizontal so that any condensate which does form will fall back into the test section. The test section pressure tap is placed such that any argon entering the test section will be carried away through the exhaust system.

The remainder of the system consists of an annular water-cooled condenser, a condensate collector tank, an ice trap to condense any mercury vapor which gets past the condenser, a mercury filter to absorb any mercury vapor which gets past the ice trap, and a vacuum pump which exhausts into the laboratory exhaust system. Since the system pressure will be below atmospheric, any leakage will be into the system, thus minimizing any health hazard from the toxic mercury vapor.

IV. CONCLUSIONS AND RECOMMENDATIONS

The steady-state evaporation experiment has been described as well as the experimental apparatus to be used for carrying out the experiment.

During the next quarter the experimental part of the work will continue. Work will also be done on improving the kinetic theory prediction of the transport coefficients.

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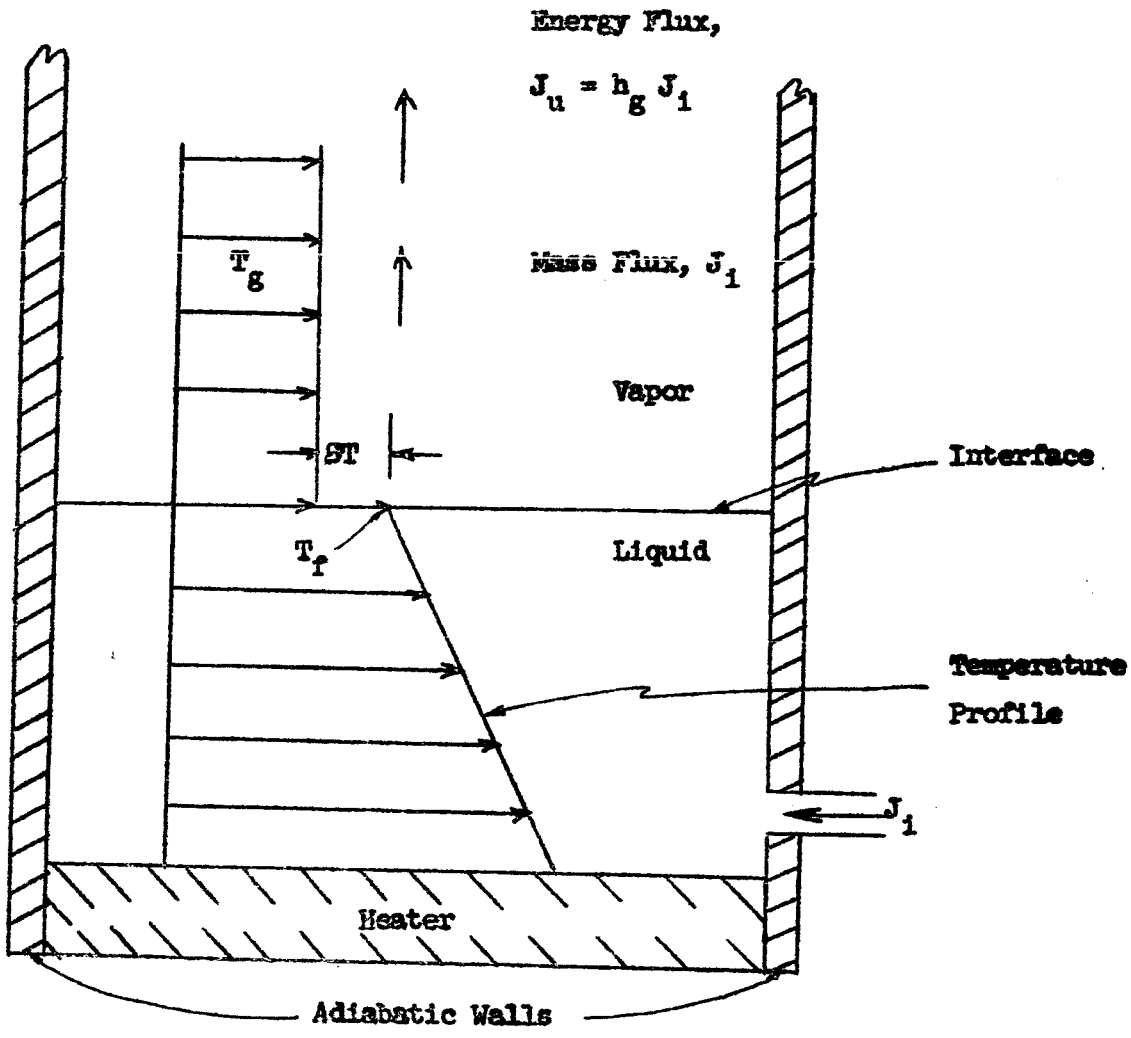

FIGURE 1 - STEADY-STATE EVAPORATION EXPERIMENT

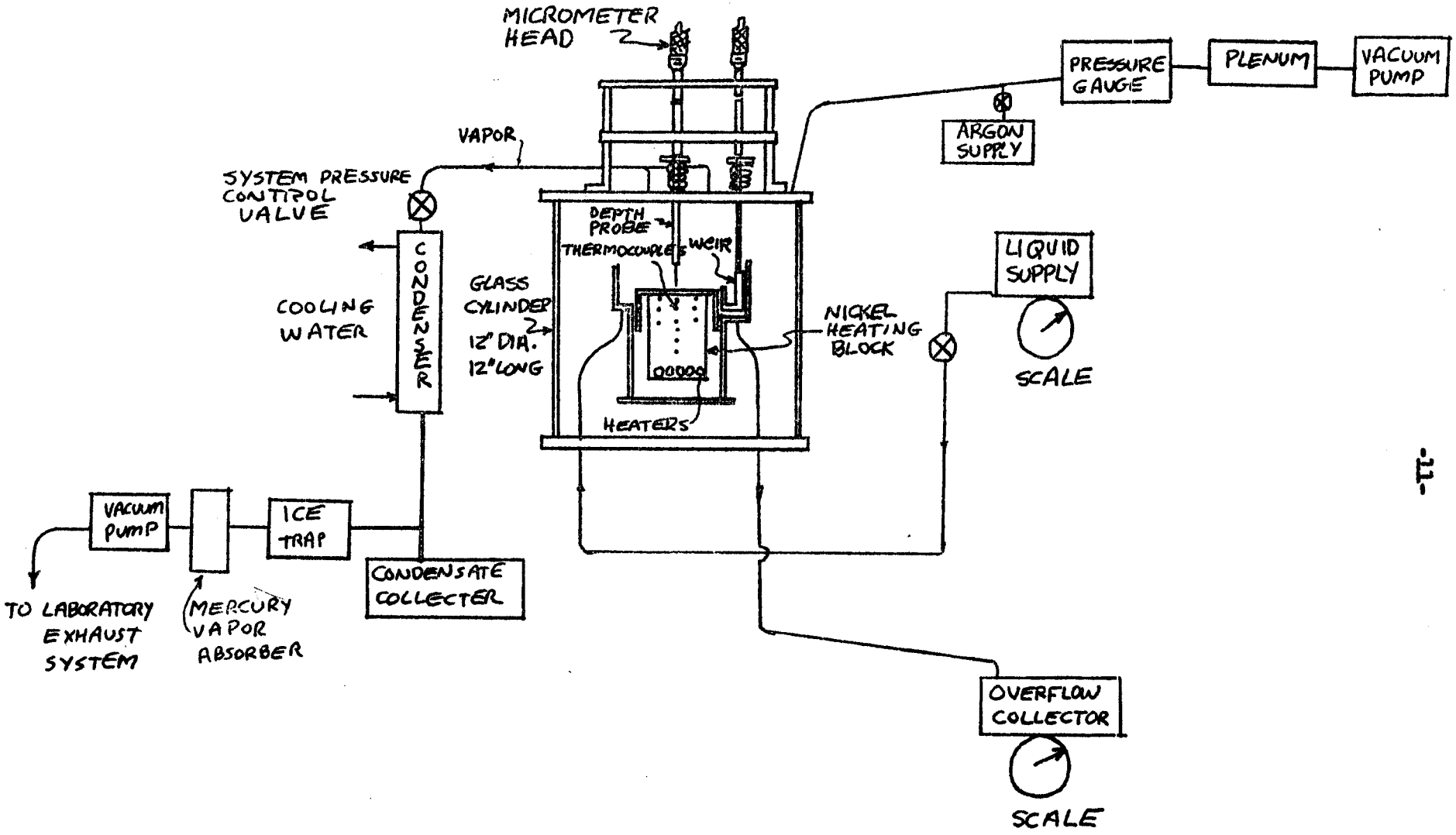

FIGURE 2 - FLOW DIAGRAM OF EXPERIMENT