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Research Paper

Methodology to construct full boiling curves for refrigerant spray cooling

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HIGHLIGHTS

- Transient temperature measurements for a liquid nitrogen spray beyond CHF were made.
- Inverse heat transfer techniques applied to obtain instantaneous heat flux and temperature.
- Methodology to construct the boiling curve beyond CHF is discussed.

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ABSTRACT

This paper proposes application of sequential function specification method to solve the inverse heat conduction problem to obtain instantaneous surface heat flux from transient temperature measurements. Transient temperature measurements beyond critical heat flux are obtained for a copper block being cooled by a liquid nitrogen spray. A method to construct the boiling curve beyond CHF is discussed. This method help in estimating the heat flux at various superheats even in the transition and film boiling region which is otherwise difficult to estimate.

1. Introduction

Film boiling is encountered in various applications like metallurgy, refrigeration, chemical and power engineering, etc. In particular knowledge of film boiling properties of coolants is of importance for nuclear reactors to assess the safety of nuclear reactor designs. Generally experimental boiling curves are obtained only until critical heat flux (CHF) as beyond this heat flux there is a vapor blanket on the surface and there is a thermal runaway situation. So conventional method of experimentation fails in the regime beyond CHF. Conventional experimental set up [1] involves controlled heat flux where heat flux is slowly increased and a stable steady state is obtained for each heat flux. But in such a set up beyond CHF, there is indefinite temperature rise. Another alternative is to have temperature controlled system [2], which would need a pressurized two phase liquid boiler to produce different temperatures. Such a system is complicated and expensive. Previous studies or reports in literature [3–10] concern mainly with extraction of boiling curves for pool boiling. Full boiling curve of saturated methanol was reported [3] for horizontal cylinders under pool boiling conditions. The possibility of cooling a superconducting magnet using liquid nitrogen, led to a report [4] of forced convection heat transfer study of liquid nitrogen inside horizontal tubes. But the study was limited to near nuclear boiling regime. Transient study of pool boiling of liquid hydrogen from a flat surface was reported [5] but limited until the critical heat flux. Numerical simulation and experiments of boiling of various cryogenic liquids were studied [6] to understand the pool boiling mechanism. Transition boiling and film boiling of FC-72 from horizontal cylinders and wires under pool boiling conditions were reported in [7]. Effect of heater orientation in liquid nitrogen pool boiling was reported in [8]. The optimal geometry of tube bundle for nucleate boiling of liquid nitrogen (over a tube bundle) was studied and reported in [9]. All regimes – nucleate boiling, transition and film boiling were reported in [10] for liquid nitrogen pool boiling over a thin wire. In summary there has been numerous studies of different cryogenic fluids under pool boiling conditions. The very limited reports on forced convection of cryogenic liquids do not fully cover the full boiling regime due to the experimental complexity at film boiling conditions. And in particular there are

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Nomenclature

d	diameter (mm)
h	heat transfer coefficient (W/m^2 K)
H	height of nozzle from chip/copper block (mm)
h_{fg}	latent heat of vaporization (J/kg)
k	thermal conductivity (W/m K)
L	length of equivalent copper block (mm/m)
N	number of spatial nodes in copper block
q	heat flux (W/m^2)
Q	heat (W)
q_m	heat flux in time interval $\lambda_{(m-1)} - \lambda_m$
r	number of future time steps
S	error function
T	temperature (°C)
t	time (s)
T_{ij}	temperature of jth node at ith time step
T_m	temperature in time interval $\lambda_{(m-1)} - \lambda_m$
x	distance along copper block from top surface (mm/m)
y	measured temperature
ϕ	sensitivity coefficient
α	thermal diffusivity (m^2/s)
$[\lambda_{(m-1)} - \lambda_m]$	time interval at time t_m
ρ	density (kg/m^3)

no reports for generating full spray boiling curves for cryogenic fluids.

So this present work proposes that measurement of transient temperature readings of a thermal run away beyond CHF, and transient temperature readings while cooling down from a high temperature to the nucleate boiling region is sufficient to estimate the boiling curve beyond CHF. There is a report [11] of similar approach to extract the boiling curve of water, but involves a complicated experimental set up, as there is a need to create a symmetrically cooled target by having twin sprays - force convection boiling on two sides of the target, in order to simplify mathematical treatment. Also the previous method required high frequency (1000 Hz) data acquisition without much noise. The present work demonstrates a novel and easyway to implement the method. The requirements of the experimental set up are simple and easy but the demonstration in the present work is done using liquid nitrogen, as this was part of a bigger research study which involved liquid nitrogen sprays. So there were some additional experimental set up required to get saturated liquid nitrogen, but for other fluids this additional experimental setup might not be required.

2. Experimental set up

A custom experimental rig was built to study liquid nitrogen spray boiling. The transient data obtained from this rig was processed to obtain the full boiling curve.

The schematic diagram of the experimental set up, showing important sensors and equipment, is shown in Fig. 1. The commercially available high pressure LGC (liquid gas cylinder), which stored liquid nitrogen at 230 psi was rented from the local supplier SOXAL. The internal cylinder pressure is used for pumping the liquid. It is to be noted that since the pressure of the liquid gas mixture is higher in the LGC tank compared to atmospheric pressure, the liquid is at the saturation temperature corresponding to the cylinder pressure and is typically at about −160 to −165 °C. When the high pressure, high temperature (1.58 MPa, −165 °C) liquid is throttled to a atmospheric pressure in the nozzle, the gaseous component is high. To overcome this problem, the liquid withdrawn from the cylinder is cooled in a heat exchanger. Since the cylinder pressure varies depending on the heat leak to the cylinder and the withdrawal rate, a pressure regulator (REGO) was fixed at the outlet of the cylinder and set at 125 psi. This high pressure, high temperature (relative to 77 K) liquid was sub-cooled in a custom-built heat exchanger. The heat exchanger was a coiled tube immersed inside liquid nitrogen filled Dewar (an insulated container to hold refrigerants). The Dewar was constantly topped up with liquid nitrogen from a commercially available 22 psi LGC tank (not shown in Fig. 1). The liquid exiting from the heat exchanger is at high pressure and at about 77–78 K. The sub-cooled liquid is transferred into the spray chamber and the distance between the heat exchanger and the spray chamber was reduced as much as possible and was approximately 300 mm, to reduce heat gain from environment 25 mm thick polyurethane insulation. All transfer lines are insulated using to reduce heat leak into the lines. A solenoid valve is placed before the entry into the spray chamber. The solenoid valve (D2062 series, Gems sensors) was compatible to liquid nitrogen temperatures because of the PTFE lining. It had an orifice diameter of 3.175 mm and a response time of 40 ms and was used to switch on/off the spray.

The spray chamber is a custom-built, double-layer vacuum-jacketed stainless steel cylindrical chamber. The vacuum jacket helps to prevent condensation on the view ports. The nozzle used was TG SS 0.7 (Spraying Systems Company) which is a full cone nozzle having an orifice diameter of 0.76 mm. A 25 × 25 mm^2 copper block served as a simulated IC chip. The heater block accommodated four 250 W cartridge heaters. It was insulated by a Teflon block on all the four sides and at the bottom. The Teflon block near the top surface had sloping edges at 45° angle to promote better drainage of the coolant. The temperatures were measured in the copper block using T type thermocouple sheathed probes (AWG 30 wire in 1.6 mm stainless steel sheath) with exposed junction for faster response to transient changes in temperature. The response time is estimated to be about 30 ms. There were three holes drilled in the Teflon housing and copper block to house the thermocouples. The thermocouples were inserted into their respective holes, which had tight fit tolerance. The measurement points of temperature were 2.8, 5.8, and 8.8 mm below the top surface at the central plane. The surface roughness of the copper surface was measured by a surface profilometer and the *Ra* value was about 0.5 μm. The chamber also had four screws to fix the position of the copper block precisely to align the copper block to the center of the nozzle/spray. The cartridge heaters were powered by a 1.5 kW DC power supply (AMREL SPS series 1.5 kW, 60 V, 25 A), which was connected to the computer through a GPIB cable to control the voltage supplied in the constant voltage mode.

The temperatures measured by the four thermocouples in the copper block, the nitrogen inlet pressure and temperature, chamber pressure and temperature were all acquired by a NI cDAQ system. A LabView program synchronized the measurements and stored all the values along with a time stamp. The program also calculated the surface temperature and actuated the valve to open or close.

The uncertainty in temperature measurement of the copper block temperature using thermocouples is estimated to be ±1 °C at liquid nitrogen temperatures. The uncertainty of thermocouple location in the copper block is 0.8 mm, half the diameter of the hole. The uncertainty in liquid temperature and ambient temperature, measured using RTD is about ±0.15 °C. The uncertainty in pressure measurement was about ±0.05 MPa, although accuracy