Flow Pattern and Heat Transfer Behavior of Boiling Two-Phase Flow in Inclined Pipes

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Movable Electrical Conducting Probe (MECP), a kind of simple and reliable measuring transducer, used for predicting full-flow-path flow pattern in a boiling vapor/liquid two-phase flow is introduced in this paper. When the test pipe is set at different inclination angles, several kinds of flow patterns, such as bubble, slug, churn, intermittent, and annular flows, may be observed in accordance with the locations of MECP. By means of flow pattern analysis, flow field numerical calculations have been carried out, and heat transfer coefficient correlations along full-flow-path derived. The results show that heat transfer performance of boiling two-phase flow could be significantly augmented as expected in some flow pattern zones. The results of the investigation, measuring techniques and conclusions contained in this paper would be a useful reference in foundational research for prediction of flow pattern and heat transfer behavior in boiling two-phase flow, as well as for turbine vane liquid-cooling design.

Keywords: liquid/vapor two phase flow, inclined pipes, flow patterns, heat transfer coefficient.

INTRODUCTION

The aim of this paper is focused on the basic applicability of liquid-cooling mechanism for high temperature turbine vanes\cite{1,2}. It is now generally known that raising the temperature before the gas turbine is one of the keys to improve the quality of gas generator. In order to extend the working range of turbine blade, it is necessary to adopt either high-temperature-resistant materials (such as ceramics) or much more effective cooling techniques. Nowadays, air is usually used as a coolant in different cooling techniques such as convection, impingement, film and composite cooling. When the temperature becomes much higher, the following problems should be considered: (a) as coolant flow increases, the amount of air flow taken from the compressor for cooling becomes more, and the overall performance of gas generator will be jeopardised; (b) increasing air flow will deteriorate gasdynamic quality of the turbine; (c) coolant passage inside the blade becomes so complicated that the manufacturing process will be much more difficult.

With the above problems in mind, the investigation introduced in this paper supposes that air can be replaced by other liquids (say, aviation kerosene) as coolant. Their advantages are as follows: (a) when cooling liquid is heated and accordingly its state changes from single phase (liquid) to two-phase (liquid/vapor), thus coolant heat transfer coefficient being augmented enormously; (b) the two-phase mixture can be supplied to combustion chamber or afterburner, and thus the waste thermal energy can be recovered and fuel atomization be strengthened so as to improve overall performance and structure of gas generator.

Two most important problems concerning engineering application in liquid-cooling should be considered, i.e., the instability range of heat transfer coefficients and the coking problem. The attention in this paper is focused on the first one.

In this work, special efforts have been made to design both MECP unit for predicting flow pattern differences, and A/D system for quick and precise measurement of wall temperature. The results show fair agreement with theoretical predictions as expected, and thus the MECP unit may be considered as a good measuring technique for engineering applications.

EXPERIMENT

The test system is shown in Fig.1 (water as
coolant). The test section, which is a uniformly heated adiabatic straight pipe (i.d. $10 \times 10^{-3}$m, o.d. $10.3 \times 10^{-3}$m, length $L = 1.24$ m.) covered with a shielded box to screen foreign signal noises, can be rotated any angle in the vertical plane. Inlet coolant mass flow is $4.2 \times 10^{-3}$ kg/s, heat flux is from $26.5 \times 10^{3}$ to $221.8 \times 10^{3}$ W/m$^2$. Experimental studies are made in two steps. Conventional cooling water and special kerosene have been used respectively.

When the test pipe is set inclined or horizontal with a boiling liquid/vapor flow in the pipe, the flow pattern distribution at the same cross section is no longer even and symmetric due to the effect of gravity. Consequently, the flow patterns at any position of the same cross section are different everywhere. Such a phenomenon will lead to varying wall temperatures and heat transfer coefficients over the same cross section.

**MEASURING METHODS AND RESULTS**

1. **Flow Pattern in Boiling Liquid/Vapor Two-Phase Flow**

Fig.2 presents a flow pattern measuring system including 3 movable electrical conducting probes (MECP) and an $X-Y$ balance drawing instrument to show flow regimes in pipe directly and conveniently by recording Volt/Time response curves as shown in Fig.3. Each MECP is made of heat resistant and enamel insulated copper wire ($0.21 \times 10^{-3}$ m.) with a "naked" point on it. The 3 bare points on MECP can be controlled synchronously to move to any position as desired. The six typical flow patterns which are combinations of those from Refs.3,5,6,7 shown in Fig.3 are used as standards with which the flow patterns obtained from the experiment measured by MECP are compared. Through the comparison with the standard flow patterns, the actual flow regime measurements by the advanced method of MECP listed in Table 1 show that such a measuring method is accurate and reliable.

This phenomenon has been observed and studied by theoretical predictions and experimental measurements, showing that heat transfer characteristics are directly associated with flow patterns[4]. So the problems investigated in this paper are: (a) how to distinguish flow pattern when coolant is heated and developed into two-phase boiling flow along the full flow path; (b) how to measure wall temperatures and correspondingly calculate heat transfer coefficients of coolant along full flow path; (c) how to correlate flow patterns with heat transfer coefficients for different flow directions (horizontal, vertical or inclined); (d) how to find the instability rule for the two-phase heat transfer.

* When aviation kerosene is used as coolant, the test system is basically similar to Fig.1, except that it should be a closed coolant system incorporating various devices: pressure bottle, valves, oil tank, condenser, connecting pipes, etc. (from point A to B is shown the initial unsteady segment)