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LOCAL HEAT TRANSFER AND CHF FOR SUBCOOLED FLOW BOILING

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Ronald D. Boyd, P. I.

TABLE OF CONTENTS

I. INTRODUCTION

Subcooled flow boiling in heated coolant channels is an important heat transfer enhancement technique in the development of fusion reactor components, where high heat fluxes must be accommodated. As energy fluxes increase in magnitude, additional emphasis must be devoted to enhancing techniques such as subcooling and enhanced surfaces. In addition to subcooling, other high heat flux alternatives such as high velocity helium and liquid metal cooling have been considered as serious contenders. Each technique has its advantages and disadvantages [1], which must be weighed as to reliabiliability and reduced cost of fusion reactor components.

Previous studies [2] have set the stage for the present work, which will concentrate on fundamental thermalhydraulic issues associated with the International Thermonuclear Experimental Reactor (ITER) and the Engineering Design Activity (EDA). This proposed work is intended to increase our understanding of high heat flux removal alternatives as well as our present capabilities by: (1) including single-side heating effects in models for local predictions of heat transfer and critical heat flux; (2) inspection of the US, Japanese, and other possible data sources for single-side heating, with the aim of exloring possible correlations for both CHF and local heat transfer; and (3) assessing the viability of various high heat flux removal techniques. The latter task includes: (a) subcooled water flow boiling with enhancements such as twisted tapes, and hypervapotrons, (b) high velocity helium cooling, and (c) other potential techniques such as liquid metal cooling. This assessment will increase our understanding of: (1) hypervapotron heat transfer via fins, flow recirculation, and flow oscillation, and (2) swirl flow.

This progress report contains selective examples of ongoing work. Section II contains an extended abstract, which is part of and evolving technical paper on single-side heating. Section III describes additional details which will be included in the first year of work. Section IV summarizes past and anticipated international interactions with investigators from other countries. Finally, Section V gives summaries of two conceptual experiments which are planned for the second and third years.

II. EVOLVING TECHNICAL PAPER

HEAT TRANSFER AND ENHANCEMENT DUE TO SINGLE-SIDE HEATING EFFECTS FOR FUSION APPLICATIONS

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Abstract

Many international engineering activities are underway to support fusion reactor implimentation for the production of economical energy in the distant future. Among the many key technological issues is the development of plasma-facing components for the International Thermonuclear Experimental Reactor (ITER) and the related engineering design activity. Such components will be exposed to single-side [i.e., internal flow channels will be heated from one side, only] heat flux ranging from 10.0 to 100.0 MW/m^2 over lengths up to 0.3 m. Although other heat transfer techniques such as liquid metal and high velocity helium cooling are being considered, subcooled flow boiling (with water) is the leading contender for high heat flux fusion accommodation. Accordingly, interest must be focused on both the local heat transfer and the critical heat flux phenomena.

Notwithstanding the voluminous technical literature on subcooled flow boiling for the case of uniform channel heating, the literature is quite sparce for conditions of single-side heating. Recently, related experimental activity involving single-side heating

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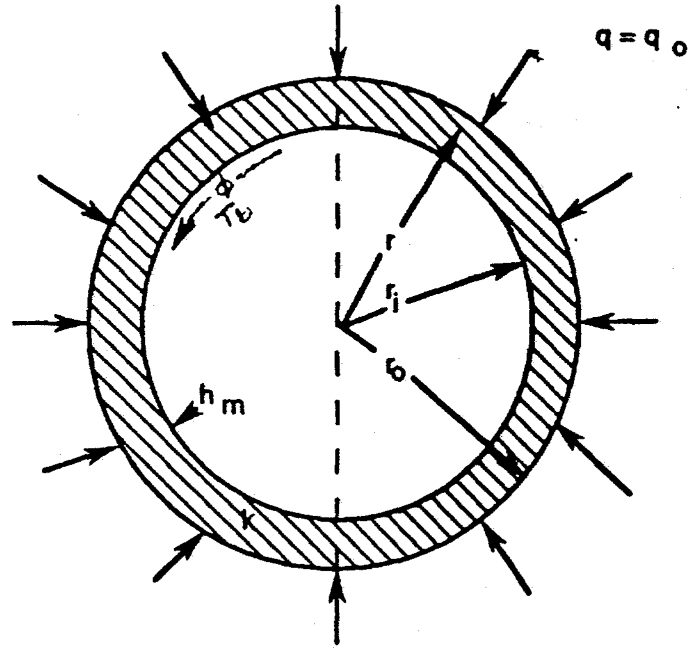
has increased. However, little work is underway to address the following questions which are essential to ITER: (1) What is the effective heat flux distribution on the inside of a channel which is subjected to a single-side external heat flux?; (2) Under what conditions can the vast literature on uniform channel heating be applied directly (without correction factors) to single-side heating?; (3) What passive enhancements will result in greater accommodation of heat flux for the single-side heated configurations?; and (4) What modification or correction factors are necessary to relate the uniformly heated channel heat transfer and the critical heat flux to that for single-side heating?

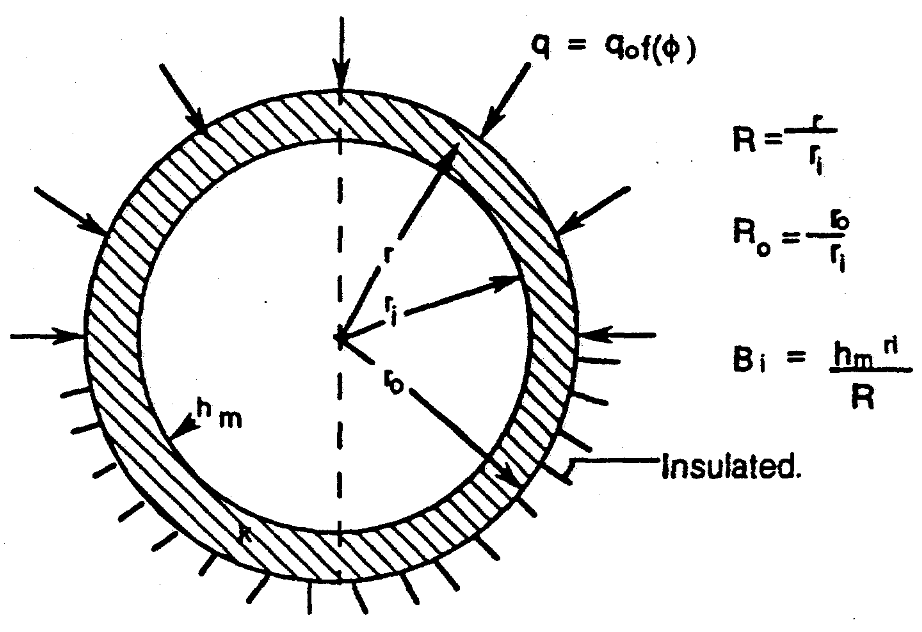
Although there are a large number of channel configurations which must be studied, this investigation will be confined to circular coolant channels (see Figure 1). For the high heat flux conditions noted above, the Peclet number will be greater than 10^5 and the Stanton number is expected to be below 0.006.

A parametric analysis was performed to examine the inside wall heat flux circumferential distribution as a function of: (1) the Biot number, Bi, which is based on the channel wall thermal conductivity, the inside radius, and the mean heat transfer coefficient, h_m (see Figure 1b); and (2) the ratio, R_o, of the channel wall outside to inside radius. Figure 2 shows an example of the channel inside wall heat flux distributions for $R_o = 1.04$ and $10^{-3} < Bi < 10^3$. For $R_o = 1.04$, the effect of single-side heating are: (1) important for $Bi > 10^{-2}$, (2) may be considered marginal for $5.0 \times 10^{-2} < Bi < 10^{-3}$, and (3) unimportant for $Bi < 10^{-3}$. Other results show that as R_o increases, these limits increase in magnitude. For example, as R_o increases to 3.0, the effect of single-side heating are: (1) important for $Bi > 0.2$, (2) marginal for $0.2 > Bi > 10^{-2}$, and (3) negligible for $Bi < 10^{-2}$. Therefore, the above results suggest that the effect of single-side heating can be characterized, with no correction factors, by uniform heating when $Bi < 10^{-3}$. The results also give insight on how to accommodate higher local heat flux and critical heat flux. However, this would require a slight alteration of the geometry of the channel.

KEY WORDS: Single-side, Enhancement, Fusion



(a) Uniformly Heated coolant channel.



(b) single- sided heated coolant channel.

Figure1: Basic Channel Heating Configurations For Fundamental Fusion Applications.

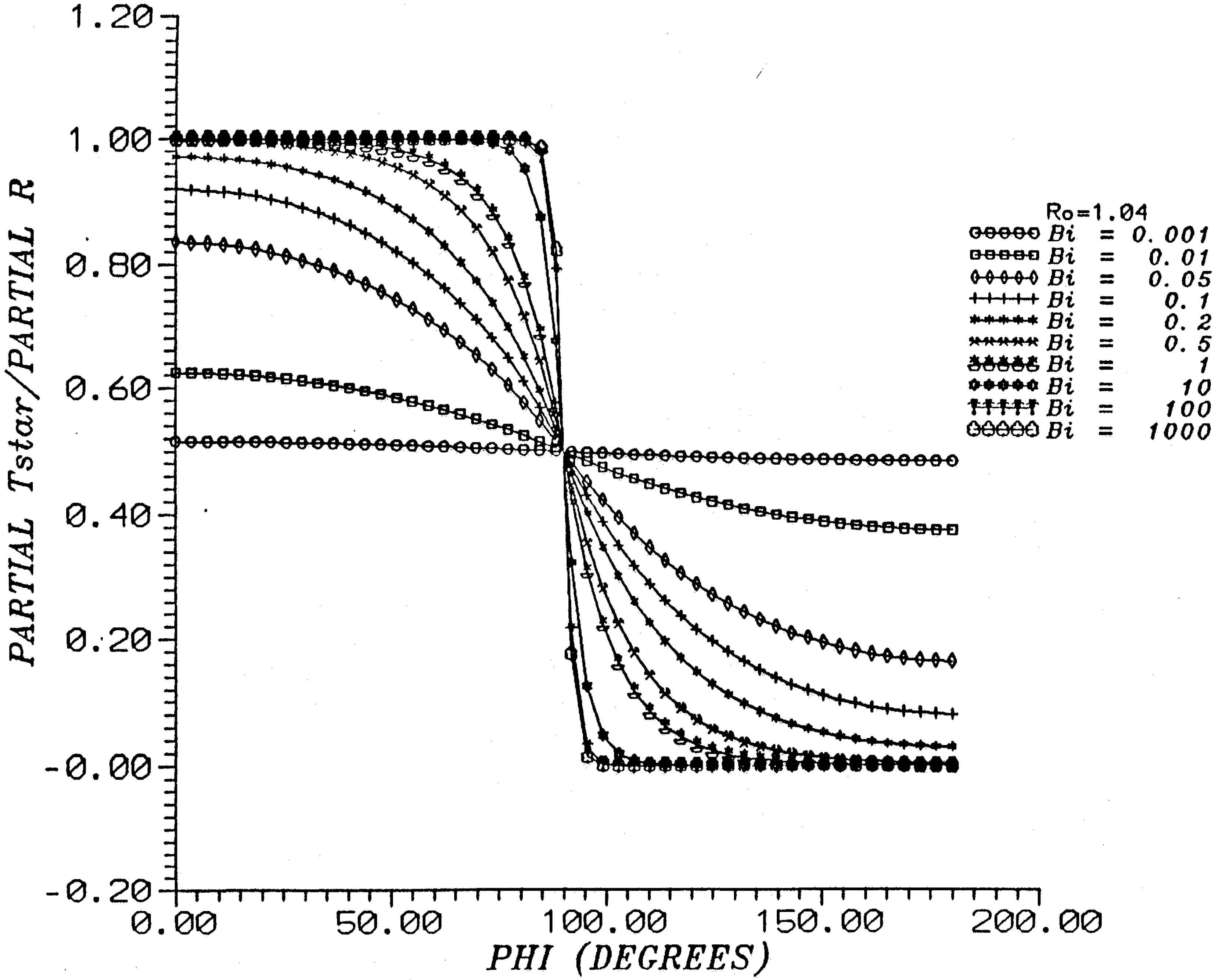


Figure 2: Dimensionless Inside wall Heat Flux Circumferential Distributions For Parameters, Ro and B i, Where $f(\phi)=1.0$, and q_o = Constant.

III. SINGLE – SIDE HEATING: ONGOING WORK

Typical examples of single-side heating analysis and experiments can be found in the work by Araki et al. [3,4], Weiberg et al. [5], Koski and Croessmann [6], and Schlosser et al. [7]. In most cases, the incident heat flux is used as a boundary condition along with a suitable flow boiling correlation (for the inside heat transfer) in a finite element analysis (FEA) code to produce an inside surface heat flux profile which is then compared with a typical CHF correlation for uniform heating. Usually, the results of the comparisons are inconclusive. That is, depending on what CHF correlation is used and the related range of flow parameters for that correlation, very good or very poor comparisons will result. There are, at least, four reasons for this uncertainty: (1) large variations in the CHF correlations, (2) many of the CHF correlations are used outside their intended applicable range, (3) the unique geometric effects of the coolant channel are accounted in the FEA but is usually not accounted for in the final comparisons, and (4) no thermal hydraulic parameters are used in the comparisons except the ratio of the heat flux. One additional practice which has resulted in much confusion and variations from one study to another is the neglect by investigators to specify whether their heat flux (local or CHF) is based at the outside or inside surface of the flow channel. For obvious reasons, most investigators assume that the CHF reported in the literature is based on the inside surface. However, some investigators do not report it in this way.

The aim of the present work is to include the unique geometric effects and the apporpriate thermal hydraulic parameters so that the final comparison between the circumferentially uniform and single-side heating configurations will include all of the above effects. In order to test the validity of properly including the these effects, the present work will be limited to the geometry of a circular flow channel, which is heated from one side by either a uniform heat flux or a cosine heat flux distribution. Dimensionless physical parameters will be identified and the resulting inside heat flux distributions will be presented in terms of these parameters. Comparisons will be made to determine correlating factors (and/or functions) between single-side and uniformly heated channels for the inside wall heat flux (and possibly the temperature and heat transfer coefficient). If sufficient single-side heat transfer data is available and if correlation factors are obtained, they will be applied to CHF data. If a consistent comparison is obtained, the results will also bo used to extend the local heat transfer flow boiling correlation for uniform heating to single-side heating [2,8].

IV. INTERNATIONAL INTERACTIONS

In addition to the invited paper [2] presented at the 2nd Specialist Workshop on High Heat Flux Components Thermal Hydraulics (Rome, Italy; supported by Sandia National Laboratories), consultation and a critical review was given to Dr. V. Tanchuk (and V. Divavin, and A. Shrubok of the Efremov Scientific Research Institute, St. Petersburg, 189631, Russia) and Dr. Robert Watson (Sandia National Laboratories, Albuquerque) on their work entitled "Ultimate Heat Flux and the Heat Removal Crisis in One-Sided Heated Channels" [9]. Ongoing collaborative E-beam experiments were discussed as well as enhancement effects such as porous coatings.

Finally, Dr. Masanori Araki (NBI Heating Laboratory, Naka-Fusion Research Establishment, Japan Atomic Energy Research Institute) will be using the Sandia E-beam facility in March, 1993 to expose bare circular channels. We plan to interact with that effort and make suggestions on additional local measurements, which will make their data useful to the present study.

V. CONCEPTUAL EXPERIMENTS

Experiment # 1: Single-Side Inside Heat Flux Measurement

The first conceptual experiment involves single-side heating of a coolant channel with an inside fluid flowing in the subcooled flow boiling regime. This effort is intended to add experimental verification or clarification to the work which is presently underway (year # 1). The present work (see Sections II and III) is intended to develop a methodology to include single-side heating effects into the predictions of local heat transfer and CHF. This experiment will provide a limited data base to test the methodology as regard to local heat transfer. The experiment will involve single-side heating of one coolant channel from one side (see Figure 1b), where the applied heat flux will be uniform or have a known profile. Circumferential temperature variations, on the outside channel surface and at selected depths within the channel wall, will be measured as functions of the applied heat flux and mass velocity. An existing code will be expanded to relate the temperature measurements to local inside surface heat flux, wall temperature, and heat transfer coefficient distributions. This data will be used along with the methodology to further: (1) examine the effectiveness of the correlation factors which relate single-side to uniforml heated channels, and (2) suggest how to extend the applicability of the existing local subcooled flow boiling heat transfer model.

Experiment # 2: Basic Hypervapotron Measurements

Among the many subcooled flow boiling possibilities of accommodating high heat flux, hypervapotrons appear to have unique advantages [10]. The current international work is not focussed on understanding the factors contributing to enhancement or design optimization. Before either of these essential goals can be realized to a meaningful degree, more fundamental work is needed. Because of the limited nature of the present funding, only a conceptual experiment can be proposed.

There is a fundamental need to learn more about the basic local heat transfer along the heated surface of a hypervapotron. Recently, some success [8] in predicting the local heat transfer has been reported. However, these results are for one isolated case and there were many unsubstantiated assumptions, which may render that approach not to be generally applicable.

This conceptual experiment involves using either a prototype or modeling fluid in the subcooled regime and flowing through a one-side heated hypervapotron-type channel. Thermocouples will be embedded in the heated surface to make temperature measurements near the heated surface and the fluid solid interface. The measurements will be used to deduce the fluid-side wall heat flux distributions for: (1) laminar and turbulent single-phase flow regimes, and (2) two-phase, subcooled flow boiling regime below the CHF. Depending on their E-beam test schedule, some of the embedded thermocouple experiments may be run at Sandia.

There have been claims [8,10] that one of the unique advantages of the hypervapotron is its ability to operate with a portion of its surface existing in the film boiling regime without burnout. Because a portion of the hypervapotron surface is always in the single-phase region, the possibility of making interferometric measurements of the local fluid temperature will be explored so that a redundant and possibly more detail heat flux distribution can be obtain around a portion of the fins. The results are expected to be useful in: (1) extending the present hypervapotron data base, (2) forming a basis for future flow visualizations for hypervapotrons, and (3) possibly presenting the first data of local fluid temperature and heat flux in the vicinity of hypervapotron fins.

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