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Experiment attributes to establish tube with twisted tape insert performance cooling plasma facing components

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HIGHLIGHTS

- Overview of twisted tape tube inserts for plasma facing components.
- Reviews historical twisted tape burn out heat flux experiments and models.
- Presents burn out heat flux model with radial pressure gradient from flow rotation.
- Compares burn out, net vapor generation, and flow excursion models for twisted tapes.
- Identifies twisted tape knowledge gaps in plasma facing applications from literature.

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ABSTRACT

The modeling capability for tubes with twisted tape inserts is reviewed with reference to the application of cooling plasma facing components in magnetic confinement fusion devices. The history of experiments examining the cooling performance of tubes with twisted tape inserts is reviewed with emphasis on the manner of heating, flow stability limits and the details of the test section and fluid delivery system. Models for heat transfer, burnout, and onset of net vapor generation in straight tube flows and tube with twisted tape are compared. The gaps in knowledge required to establish performance limits of the plasma facing components are identified and attributes of an experiment to close those gaps are presented.

1. Introduction

Twisted tape inserts have often been used to enhance the performance of tube cooling assemblies in applications where heat fluxes in excess of $10^6\,W/m^2$ are expected. The twisted tape insert rotates the internal liquid flow, and adds to the wetted area in the tube. The flow rotation adds a radial pressure gradient to the flow, and induces secondary flows. The twisted tape inserts enhance the nominal heat transfer, and increase the critical heat flux (CHF) over that in an open tube with identical mass flow. The twisted tape insert also increases the pressure gradient in the tube, as do most other heat transfer performance enhancement approaches. However, the twisted tape insert can provide improved heat transfer and improved burnout heat flux over that of an open tube with identical inlet subcooling and applied pressure drop. This makes the tube with twisted tape insert the most efficient solution for many high heat flux cooling applications.

Twisted tape inserts may be used in the cooling tube assemblies in plasma facing components (PFC) for magnetic confinement fusion experiments. The cooling technology is employed with monoblock technology that can be deployed across common inlet and outlet flow delivery plena. Each series of monoblocks is attached to a tube with a twisted tape insert, and active cooling can be achieved by linking these tubes in various flow configurations. One such flow configuration can be seen in Lumsdaine et al. [1], where active cooling of a so-called “scraper element” is investigated. In this case, the most appropriate flow configuration was determined to be the case with six parallel flow channels. Each parallel flow channel was made up of one single “module,” which contained four individual monoblock “fingers” as seen in Fig. 1. The serial flow in the modules was connected by 180° turns in the flow. While design details of the scraper element remain

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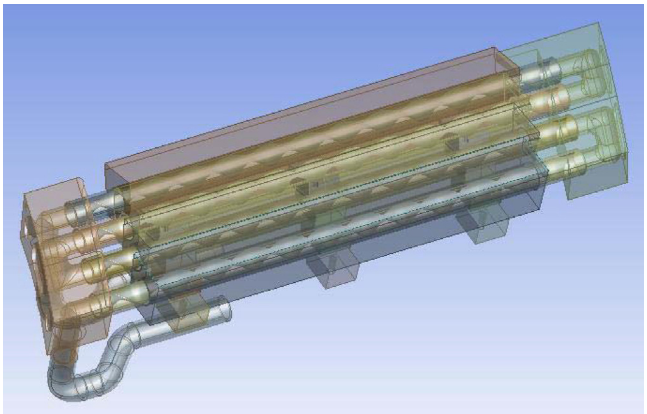

Fig. 1. Model of single four-finger module.
Source: Ref. [1].

flexible, the following parameters serve as an approximate baseline for considerations in this paper. The inlet pressure for the finger flow is approximately 2 MPa and the exit pressure is anticipated to be 1.5–1.8 MPa. The inlet flow temperature is 20 °C. The tube diameter is 12 mm with the tape insert making a full turn in each 48 mm of axial flow length. The inlet mass flux is near 10,000 kg/m^2s. Flow boiling with fluid bulk temperatures well below saturation is expected during service, with peak thermal fluxes of order 10^7 W/m^2.

Historical assessment of twisted tape performance spans six decades, and focuses on global systemic parameters such as heat transfer coefficient, pressure drop, and CHF or burnout (BO) heat flux. The reduced order engineering models developed during these years are conventional, and have some mechanistic basis, but also retain many correlation constants that are tuned to data from narrow operational envelopes. While some data are available for non-uniform heating, most of the data supporting modeling of tubes with twisted tape inserts are for uniform flux in Joule heated tubes.

This paper first reviews existing knowledge from legacy experiments and associated models with a focus in the cooling performance prediction for the plasma scraper modules. We then identify what additional knowledge is needed to support thermal modeling and performance limit prediction for PFC design. These knowledge gaps are used to define key attributes of a conceptual experimental campaign.

2. Twisted tape experiment history

The history of twisted tape thermal performance experiments is reviewed with attention to the design of the experiments, and the manner of flow delivery. The majority of previous experiments used Joule heating of the tube to provide relatively uniform heat flux. The models derived from those experiments are presented for the flow, flux, tape twist and pressure expected in the scraper element cooling application later in this paper.

Bergles and Kuzma-Kitcha [2] reviews the history of twisted tape experiments and modeling. Twisted tape experiments in water are considered. The attributes of experiments are consolidated in a table with attention to manner of tube heating, the tube material composition, the dimensional attributes of the tube and tape, and attendant mass flux and pressure conditions for testing. The review offers a discussion of some bothersome aspects of the data such as premature CHF or BO. Some of these events were allegedly due to local insulation of tube wall by the tape. Some discussion of non-uniform circumferential heating experiment results is also offered, which is germane to the fusion divertor application. Discounting premature CHF outcomes in some experiments, the CHF in non-uniform azimuthal experiments is higher by 40–80 percent over the uniformly heated cases.

Of particular interest are the pressure drop versus applied power characteristics of the tubes, and attendant importance to so-called hydraulic induced instabilities such as the Ledinegg instability [3] and pressure drop oscillations. Only two prior experiments addressing these phenomena are discussed for the twisted tape insert. Both of these used uniformly heated tubes.

Also discussed is the analogy of the twisted tape flow behavior to straight axial flow behavior with respect to thermal limits and heat transfer near the initiation of boiling.

Gambill et al. [4] tested tubes of copper, aluminum and nickel with twisted tape inserts. Tube diameters ranged from 3.45 to 10.2 mm ID. Inlet axial velocities ranged from 4.57 to 47.55 m/s. Most of these tubes were swaged onto an Inconel tape 0.38 mm thick, and the test sections were heated with AC electrical power. Tap water was used for these tests. This manner of fabrication is consistent with that later used by Lopina and Bergles [5], reviewed later.

Gambill et al. [4] note radial acceleration due to fluid rotation will elevate pool boiling heat flux at burnout according to acceleration to power ¼, and explore this mechanistic approach for correlating BO experiment outcomes. Three correlation approaches are ultimately explored for BO data, and they ultimately choose another correlation as the preferred model. Gambill et al. [4] had to move thermocouples off of the tape edge locations because of “aberrant measurements”. They ascertained the thermocouples giving the aberrant readings were on the edge of the tape using X-ray examination. The aluminum, copper and nickel tubes all have high thermal and electrical conductivity. All tubes were electrically heated with AC power, and the Inconel tape may have shared in heating the water depending on the degree of electrical connection retained at the operating pressure and temperature. No difference was noted or apparent in the heat transfer and BO data of the three tube materials.

Lopina and Bergles [5] compared subcooled boiling heat transfer and pressure drop in a straight tube with and without twisted tape inserts. Tests were conducted with demineralized and degassed water at low pressure with tape twist ratio, y, defined as the axial distance required for the tape to turn 180° divided by the tube inner diameter, between 2.48 and 9.2. The tubes were redrawn over the twisted tape to a final diameter of 4.93 mm with an embedded depth of 0.05 mm, so that there was no gap, resulting in the tape being 4.93 mm wide and 0.36 mm thick. The test section pipe was nickel (Inco Alloy 200) while the tape was Inconel (Inco alloy 600) and was heated by DC electricity, which resulted in heat fluxes in the range of 0.38–0.88 MW/m^2. They found that the systematic heat flux effects during subcooled boiling “that wall superheats from swirl flow are not any higher than those for straight flow.” This agreed with other studies at heat fluxes above 0.16 MW/m^2. They also showed that although twisted tape increased the pressure drop threefold at some heat fluxes, the burnout heat flux at equal pumping power is larger. They also visually observed bubbles condensed as they were removed from the superheated wall layer.

Manglik and Bergles [6] examined the friction factor and Nusselt number in turbulent flow with twisted tapes and developed generalized correlations. The studies utilized water ($3.5 < Pr < 6.5$) and ethylene glycol ($68 < Pr < 100$) with twisted tape inserts having $y = 3.0, 4.5, 6.0$ at flow rates corresponding to $300 < Re < 3 \times 10^5$. They measured cooling and heating conditions along a section with $L/D = 144$ ($d = 21.18$ mm) which followed a calming section, $L/D = 72$, to ensure fully developed flow in the test section. It was concluded that the increased heat transfer and increased axial pressure drop with twisted tape inserts was due to tape induced vortex