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Isothermal velocity measurements in two HyperVapotron geometries using Particle Image Velocimetry (PIV)

A. Sergis [a,*], Y. Hardalupas [a], T.R. Barrett [b]

[a] The Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK
[b] CCFE, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK

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ABSTRACT

HyperVapotron beam stopping elements are high heat flux devices able to transfer large amounts of heat (of the order of 10–20 MW/m^2) efficiently and reliably making them strong candidates as plasma facing components for future nuclear fusion reactors or other applications where high heat flux transfer is required. They employ the Vapotron effect, a two phase complex heat transfer mechanism. The physics of operation of the device are not well understood and are believed to be strongly linked to the evolution of the flow fields of coolant flowing inside the grooves that form part of the design. An experimental study of the spatial and temporal behaviour of the flow field under isothermal conditions has been carried out on two replicas of HyperVapotron geometries taken from the Mega Amp Spherical Tokamak (MAST) and the Joint European Torus (JET) experiments. The models were tested under three isothermal operating conditions to collect coolant flow data and assess how the design and operational conditions might affect the thermal performance of the devices for single phase heat transfer. It was discovered that the in-groove speeds of MAST are lower and the flow structures less stable but less sensitive to free stream speed perturbations compared to the JET geometry. The MAST geometry was found to suffer from hydrodynamic end effects. A wake formation was discovered at the top of the groove entrance for the JET geometry, while this is absent from the MAST geometry. The wake does not affect significantly the mean operation of the device but it may affect the coolant pumping load of the device. For the JET variant, there is evidence that the typical operation with free stream flow speed of 6 m/s is advantageous.
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1. Introduction

HyperVapotron (HV) beam stopping elements are durable, highly efficient two phase heat exchangers, which are able to withstand high heat fluxes (HHF), in excess of 10 MW/m^2, in steady state [1]. They were developed by Thomson CSF during the 1950s' to cool the anodes of high power tetrodes employed for communication purposes in klystron microwave tubes [1,2]. They have high geometric flexibility and can be moulded to the shape of the heat exchanging surface they are attached to. These factors make them viable for nuclear fusion applications as plasma facing components (PFC), hence their use in recent fusion reactor cooling studies. However, other conventional high heat flux transfer applications might also be benefited from their properties. HVs currently used are extensively on the Joint European Torus (JET) for all actively cooled neutral beam dumps and are being considered in the design of the next step international device, ITER (International Thermonuclear Experimental Reactor) and DEMO (DEMOnstration power plant) [1,3].

HVs consist of three main features. A high velocity free stream rectangular channel, which is joined over a substrate with grooves running perpendicular to the free stream flow, and a longitudinal groove running along each rib of the device (see Fig. 1). The device is oriented in a way that the grooved substrate is facing the oncoming heat flux. HVs employ the "Vapotron" effect – a complex, highly effective 2-phase heat transfer mode, which allows some parts of the device to operate with higher surface heat flux than the local critical heat flux (CHF) [4]. The operation of the device is characterised into three modes according to the heat flux received under given operating conditions (pressure and flow rate). These consist of a low power single phase heat transfer mode, an intermediate power 2-phase soft boiling regime mode and a high power hard boiling mode at which parts of the device (HHF facing wall) operate above the CHF point [1]. Irregular vortices form along the grooves, which appear to play an important role in the performance of the device. Upon the latter two modes of operation, at the onset of boiling, vapour bubbles form inside the grooves followed

* Corresponding author.
E-mail address: a.sergis09@imperial.ac.uk (A. Sergis).

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by an injection of the vapour in the free stream, which then gets conveyed downstream and condenses.

In recent studies, various Computational Fluid Dynamics (CFD) and experimental work has been performed by research groups around the world to assess the applicability of HVs in fusion applications [1–26]. The experiments are generally focusing on the overall thermal performance of various geometries under various thermal loading scenarios and operating conditions, while the CFD studies in general try to recreate the experiments in an effort to model the operation of the device and hence be able to predict the thermal performance under expanded operation regimes and geometries without the need of further experimentation for design optimisation.

In the literature, only a handful of experimental and computational investigations provide information regarding the structure of the flow field inside a HyperVapotron. An experiment has been performed in the past [26] to provide qualitative information regarding the flow vortical structure observed in a single groove of a HV. However, this experiment remained a qualitative investigation and the data cannot be used to evaluate the corresponding CFD investigations that either followed or preceded it [4,23]. An experimental visualisation of the vapotron effect under all of the thermal power modes of operation has also been performed [5]. However, there is no detailed analysis of the recorded data to be able to evaluate the complex vaporisation, steam convection and condensation processes presented in the computational studies. The hydrodynamic flow structures evolving in the device have not been studied in detail experimentally and hence the physics of heat transfer, which are strongly related to the coolant flows, are not yet fully understood.

This paper is a significant expansion of our earlier work [27] and addresses the temporal behaviour of the isothermal flow field inside the grooves of a HV, which is important for the single phase heat transfer mode that initiates the 'Vapotron' effect during hot operation. This should enable a better understanding of both the design aspects and operation regimes of the device, as well as a better understanding of the initiation of the 'Vapotron' effect by analyzing the single phase heat transfer in the device before the vaporisation and ejection processes take place. Two geometries are investigated which relate to HV geometries found on JET and the Mega Amp Spherical Tokamak (MAST) [26] fusion facilities. Both geometries are evaluated under three operating conditions, which are defined by the free stream speed of the flow inside the devices, with one of them being the typical operating condition on both fusion experiments. The current paper builds on the preliminary results published in [27] by presenting a wide range of experimental results for a range of flow regimes. Quantitative temporal and spatial flow analysis is applied to the instantaneous measurements, including Proper Orthogonal Decomposition (POD) of the instantaneous flow distribution and image recognition of the instantaneous vortical centroid structure present inside the grooves of the HV. These results quantify the stability of the flow structures and evaluate consequences on the performance of the HV.

2. Methodology

2.1. Experimental rig

2.1.1. Test section

Two high optical quality transparent test sections were designed to model the JET and MAST related HV geometries (Fig. 2) [27]. The model is shortened to reduce experimental cost and complexity; it consists of five grooves. The choice of the number of grooves follows similar modelling principles as those found in other experimental modelling studies (i.e., at least three geometric repeats to deal with end effects when monitoring the middle one). This was also confirmed by the results of the experiment to follow.

The test sections were designed to have a well-conditioned, "top hat" inlet velocity profile by introducing flow straighteners and grids followed by a contraction with area ratio of 5 for the JET variant and 14 for the MAST variant inside the flow conditioning section of Fig. 3 upstream of the transparent test section. A diffuser was also added downstream of the test section to ensure that the downstream flow was also well conditioned. In addition, the operational scenarios tested and the experimental process followed required a high volumetric flow rate to be delivered at the test section with minimal vibrations. To achieve that, the rig was split into two main functional components, namely the pumping station and the measurements station, both connected into a closed circuit loop using flexible hoses. The pumping station comprises of a collection tank, a pump able to deliver volumetric flow rates up to 350 l/min, additional flow volumetric and pressure control vanes, electrical circuitry and pressure gauges to finely tune

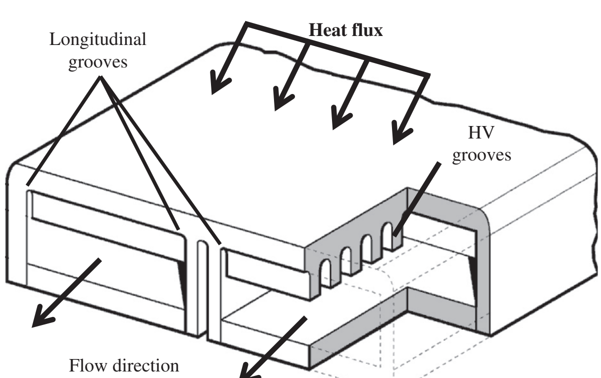

Fig. 1. Schematic of a complete HyperVapotron element with a cut out section revealing the transverse grooves.

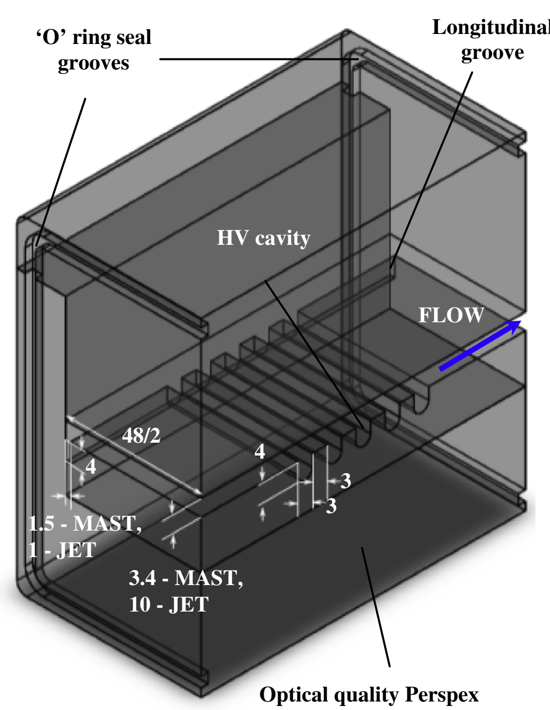

Fig. 2. Dimensionalised centre-line sectional view of the HV test sections under consideration. Dimensions are in mm.

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