An review for the heat transfer researches of Hypervapotron in the ITER first wall

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Abstract. For the steady running of the first-wall (FW) in international thermonuclear experimental reactor (ITER), it’s essential to introduce highly effective heatsinks which can bear high heat flux and remove it up to 30MW m⁻². Hypervapotron (HV) is one of the most promising devices in which the subcooled boiling plays a significant role. In this work, notable conclusions drawn by other researchers have been summarized, like “Vapotron effect” and “appearance of vortex”. Characteristics of different HV fabrications were compared at the same time. Especially, aiming at the optimization of Hypervapotron test section for FW in ITER, a series of selected HV heat transfer experiments were analysed thoroughly, including the working fluid parameters, structures of test section, CHF test results, etc. The most reasonable and reliable design of the test sections and corresponding parameters were chosen and optimized.

1. Introduction

With the development of fusion technology, like the international thermonuclear experimental reactor (ITER), the demand for devices that can stand high heat flux and have tremendous heat transfer performance is getting stronger with time goes by. The first wall device, divertor dome, and calorimeter in ITER will face an incident heat flux up to 30 megavolts per square meter [1]. Therefore reliable heatsinks should be applied to make sure the safe running of the fusion reactors. Many good-designed heat removal components have already been proposed and tested, such as Swirl tube, Screw tube, Jet cooling, Pin-fins, etc. Among all these devices, Hypervapotron is a promising and satisfying option as a result of efficient heat flux removal performance during the fully subcooled boiling regime.

The concept of Vapotron was first time introduced by Fran et al. in 1958 [2]. Thomson-CSF Company developed a fin cooling with Vapotron effect and created Hypervapotron in the 1970s. Huang [3] conducted an HV experiment under high heat flux with the help of planar laser-induced fluorescence technology (PLIF), concluding that subcooled boiling prevails and contributes the most amount of heat removal but not single-phase convection. From the development of the boiling process, which more clearly shown in the boiling curve, a critical heat flux (CHF) will eventually be reached with the augment of superheat. The heat transfer deterioration will happen if the superheat of the heated surface is relatively high and this will lead to a steep rise of surface temperature, a rapid reduction of heat transfer coefficient (HTC) and “burnout” of the component will be caused at the end which is a catastrophic accident in actual engineering projects. Furthermore, compared with saturated boiling, subcooled boiling has a higher heat transfer efficiency and critical heat flux, which has been confirmed experimentally. More than 40% extra CHF has been acquired by the usage of Hypervapotron than traditional smooth tubes or channels [2]. Consequently, it is fair enough that HV, which’s usually
manufactured with copper alloy, such as Cu-Cr-Zr [4], can be one of the most promising candidates working on high heat removal.

Different from other devices, the outstanding heat transfer performance of HV should be explained by a distinctive “Hypervapotron effect”. Cattadori [5] illustrated this phenomenon and generalized as follows: With the constant highly heating at fin root, the liquid between adjacent fins is allowed to boil and produce steam that will eventually fill up the slot. The steam is so hot that it will undergo a quick condensation in the subcooled bulk liquid, emptying the slot and easing their replenishment with cold liquid. After that, the heated surface will be rewetted. This continuous boiling and condensation process between adjacent fins allows enhancement of the CHF.

In Wang’s [3] and Chu’s [6] studies, images of instantaneous vortex interaction with the bulk flow in triangular fins and grooves were recorded by high-speed camera (HSC) and particle image velocimetry (PIV), indicating that the existing of vortex may promote HV effect. A similar conjecture was also made by Falter et al. [7] from JET. Over more than thirty years safe running in JET, Hypervapotron was considered as simply a vortex flow promoter in addition to an area-extended heat exchanger. While through the comparative heat transfer experiments of HV and smooth plain channel conducted by Chen [2], Obviously, the trends and different regimes of the boiling curve indicated that HV fabrication does not change the mechanism of subcooled boiling but delay the emergence of deterioration and improve the CHF value relatively depending on specific thermal-hydraulic conditions.

By far it’s still not clear that the HV heat transfer mechanism on account of its complex designs and phenomena. Whereas, the prediction of CHF along with a clearer understanding of HV heat transfer characteristics has a great significance of guiding the application in actual engineering, ensuring maximized usage of HV performance, and avoiding a “burnout”. A summary of researches concentrating on HV heat transfer was written in this review and a HV test section design was supplied at the end for the future experiments to be conducted.

2. The Key conclusion drawn by prior studies
Those most important conclusions in prior analyzed studies should be summarized in order to guide the design of HV test section and have a more rigorous analysis for the future received data in addition to special phenomena. Here are some keys:

Hypervapotron does not change the fundamental mechanism of subcooled boiling, either enhance HTC to a much higher degree, while it can help to postpone the occurrence of heat transfer deterioration [2]. In other words, a relatively high heat flux can still be maintained at a higher superheat. HV can be treated as a vortex promoter or turbulence generator, and the existence of vortex and turbulence maybe can be an explanation for this character.

“Hypervapotron effect” is another important factor that makes HV itself so distinctive. Due to the need to maintain the occurrence frequency of HV effect, we should keep a relatively low bulk flow velocity and subcooling of working fluid [5]. And for these particular reasons, they limited the maximum of CHF in Hypervapotron.

Before acknowledgment of exact CHF value, it was recommended by JAERI [8] that a temperature increase trigger is essential for avoiding the occurrence of “burnout” and protecting the safety of the experiment devices and researchers. The speed of temperature increases at the heated surface may be far more out of our expectation, so a relatively low incipient trigger temperature should be set, and then it should be adjusted step by step with the help of empirical prediction formula.

When the feed water flows into Hypervapotron from the circular tube, a pressure drop will be caused, which had been proved by JET [7]. So this pressure drop caused by the change of channel structure will be taken into account when the design of the test section will be conducted.

3. CHF experiments summary
Efremov Institute [9] carried out thermal-hydraulic experiments to define CHF for a range of possibly realized water parameters for first wall cooling. With the help of the infrared picture, the heat load absorbed by the test section surface was defined as the value of CHF, at which the surface temperature
of the test section could not stay steady but started to soar sharply. Calorimeter, thermocouples (imbedded under the surface 1.5 mm) were applied to measure the heat flux and mock-up temperatures, respectively. In this way, an CHF for reference was defined as 8.2 MW m$^{-2}$ (P = 2 MPa, T$_{out}$ = 140 °C, V = 2 m s$^{-1}$). The heat load was absorbed step-wisely, i.e. from 1 MW m$^{-2}$ to 8.2 MW m$^{-2}$. When it reached to 4.8 MW m$^{-2}$, the signal of thermocouples started to become unstable, which was caused by the appearance of film boiling. The overall working fluid parameters are as following: inlet temperature T$_{in}$ = 70-100 °C, working pressure P = 2-3 MPa, flow velocity V = 1-4 m s$^{-1}$.

SNL [10] performed a series of the CHF test for Hypervapotron used in ITER divertor vertical target. An effective method was provided to obtain as much critical data as possible with a minimum amount of time. Their experiments start with the least aggressive cooling (relatively high inlet temperature, low pressure and low flow velocity), and then increased the pressure and flow velocity but decreased the inlet temperature step by step until the most aggressive cooling was reached.

The report presented by JAERI [8] included the CHF experimental results of Hypervapotron. They used thermocouples embedded in the heated surface of Hypervapotron to detect CHF. An advanced trigger temperature was set, and if within 200ms the temperatures soar so rapidly that even reach or exceed the value of trigger setting, the corresponding incident heat flux will be recorded as CHF, and the heating device will stop to avoid burn-out. The working pressures are 0.7, 1.0 MPa, inlet temperatures are from 26 to 31 °C, flow velocities are from 2 to 10 m s$^{-1}$. Consequently, the CHF values are from 6.8 to 25.3 MW m$^{-2}$.

In the experiment of Wang [11], the heated surface temperature of the test section was recorded with the help of the correlation between temperature and the grey level of the image taken by HSP (High-speed photography) and PLIF (Planar laser-induced fluorescence).

JET [7] has a long history using Hypervapotron heat sink as “beam stopping elements”. It can be concluded that peak power density up to 30 MW m$^{-2}$ could be removed after a series of tests in JET. In all the experiments of JET, flow parameters were set as follows: flow velocity ≤ 11 m s$^{-1}$, inlet pressure ≤ 1 MPa, inlet temperature ≤ 50 °C. Almost all the Hypervapotron used in JET applied with the same structure, which can stand CHF as 15 MW m$^{-2}$ when the flow velocity is 3 m s$^{-1}$. A vertical structure was chosen as fluid inlet manifold, which significantly reduced the space requirement and met the need of two parallel channels.

G.Cattadori [5] did a groundbreaking piece of research for heat transfer in Hypervatron. For the test section in this work, when the working pressure = 0.9 MPa, flow velocity = 9 m s$^{-1}$, and T$_{in}$ = 60 °C, the maximum CHF = 29.4 MW m$^{-2}$ was obtained. Phani.D [12] carried out a typical experiment for subcooled boiling in Hypervapotron, the CHF value was not reached, but two high heat flux data for different flow parameters were gotten: V = 11.5 m s$^{-1}$ (7.89 m s$^{-1}$), P = 5.7 bar (7.8 bar), T$_{in}$ = 20 °C (50 °C), the HHF are approximately 18.5 and 27 MW m$^{-2}$, respectively. Lin [13] used the hot-spot model to predict CHF value, which is 0.99 MW m$^{-2}$, and then compared it with the experimental boiling curve that showed a reached CHF value as 0.89 MW m$^{-2}$. The flow parameters for Lin’s experiments are 0.6 MPa for pressure, 20 °C for inlet subcooling, and 0.16m/s for flow velocity.

Under special thermal-hydraulic conditions (P = 0.6 MPa, G = 186 kg m$^{-2}$s$^{-1}$, inlet subcooling = 30 °C) Chen [2] reported results of a typical heat transfer experiment, which showed that CHF value was approximately 0.85 MW m$^{-2}$. At the same time Chen carried out a series of experiments especially for the fully developed boiling process, which is corresponded to the following parameters: Pressure from 0.5-0.8 MPa, Mass flow rate 186 or 310 kg m$^{-2}$s$^{-1}$ and inlet subcooling 10, 20 or 30 °C).

Youchison [14] tried to investigate the influence of different Hypervapotron geometry on its thermal-hydraulic performance. Experiments using 70 °C inlet water at 2.7 MPa applied mass flow rate of 435 g s$^{-1}$ and 263 g s$^{-1}$ on Hypervapotrons with the 5 mm and 3 mm backchannel, respectively, which provided an average flow velocity of 2 m s$^{-1}$ in both backchannel. Results showed that CHF values are approximately 11.8, 8.6, and 8.4 MW m$^{-2}$ for different widths of 36, 50, 70 mm. There are two types for 50 mm width Hypervapotron which CHF were tested with the 5mm backchannel: 2 mm and 4mm teeth heights. The corresponding CHF are 9.3 and 9.5 MW m$^{-2}$.
In the experiments of Phani.D [15], flat rectangular channel and Hypervapotron test section were both tested with the help of Calculational Fluid Dynamics (CFD) and the CFD results were compared each other, at the same time, compared with the Mock-up experimental results from Efremov Institute. The experimental inlet condition Hypervapotron test section, are pressure 2 MPa, inlet temperature 110 °C, flow velocity 1-4 m s⁻¹, and they confirmed that in this typical situation, the flow is always turbulent and its corresponding Reynolds number is approximately 50000 for 1 m s⁻¹. The CHF value was about 9 MW m⁻² for 2 m s⁻¹ and incident heat flux 5 MW m⁻², while for the flat channel under the similar parameters, the corresponding CHF was only 5 MW m⁻².

Hou [16] and Zhao [17] conducted an CHF experiment for both flat plate and Hypervapotron inside a heater block which could change the inclination angle itself. Previous study of authors had indicated that under boiling condition the CHF value will gradually increase with the aging of the heated surface, and finally a plateau will be reached after approximately 8-9 h of boiling. At the basis of 10 h pre-aging process, the CHF experiment was conducted, and results showed that under pressure 0.1 MPa, average inlet temperature 95 °C, mass flux 31.9 kg m⁻² at 10 degrees position, CHF is 0.61 MW m⁻²; while for mass flux 120.9 kg m⁻² at 70 degrees position, CHF is 2.15 MW m⁻².

Youchison [18] performed a series of tests on rectangular channels in the vacuum chamber and CFD simulation for Hypervapotron at the basis of the mockup results received by Efremov Institute. The experimental flow parameters of 1 m s⁻¹ water at 115 °C inlet temperature and 2 MPa of pressure were used as boundary conditions in the simulation. From the calculational result, it was clear to see that surface temperature at the centerline and sides of the heated surface were much higher than average. At the same time from the test with a rectangular channel, a prominent indicator was got that below CHF steady-state temperatures are quickly achieved, while above CHF there are no steady results. According to this indicator, the results of simulation and experiment showed that CHF was approximately 10 MW m⁻² (lower than 10 MW m⁻²).

The enhanced heat flux FW mock-ups which were manufactured by Russia and China were tested under HHF loads in the electron beam facility JUDITH1 in FZJ [19], Germany. Owing to the operational restriction of the testing facility, the working fluid of flow velocity 4 m s⁻¹ at room temperature, and 1.8 MPa of pressure were chosen as the coolant. Under those given flow parameters, a 4.0 MW m⁻² HHF can be removed.

The summarized experimental data was shown in the table 1.

Table 1. Experimental CHF data for subcooled boiling in Hypervapotron during one-side heating.

| Source | Flow velocity, m s⁻¹ | Inlet temperature, °C | Working pressure, MPa | Mass flux, kg m⁻² s⁻¹ | CHF, MW m⁻² | HV structure |
|--------|----------------------|----------------------|-----------------------|-----------------------|-------------|--------------|
| [8]    | 2-10                 | 26-31                | 0.7, 1.0              | -                     | 6.8-25.3    | Groove       |
| [13]   | 0.16                 | ≈139                 | 0.6                   | -                     | 0.89        | Groove       |
| [2]    | -                    | 122-(128)-160        | 0.5-(0.6)-0.8         | (186), 310            | (0.85)      | Groove       |
| [17]   | -                    | 95                   | 0.1                   | 31.9,120.9            | 0.61,12.15  | Groove       |
| [9]    | 1-(2)-4              | (70)-100             | (2)-3                 | -                     | (8.2)       | Scraper      |
| [18]   | 1                    | 115                  | 2                     | -                     | =10         | Scraper      |
| [7]    | (3)                  | ≈50                  | ≈1                    | ≈(15)                 | Scraper     |
| [14]   | 2                    | 70                   | 2.7                   | -                     | 8.4-11.8    | Scraper      |
| [15]   | 1-(2)-4              | (110)                | (2)                   | -                     | (9)         | Scraper      |
| [5]    | (9)                  | (60)                 | (0.9)                 | -                     | (29.4)      | Out-finned tube |

From the CHF experiments performed by JAERI [8] and Efremov Institute [9], which were shown in figure 1, it is clear to foresee that with the increment of flow velocity, the overall (middle, inlet and outlet part of test section) average critical heat flux will increase at the same time.
4. Features of HV fabrication

During the designs of HV test section, several significant features that should be taken account of are as follows (figure 2): (1) Fin structure, fin height, fin width, pitch (2) Height of backchannel (3) Width of coolant channel (4) Teeth separated from / connected to sidewalls (5) Width of side slot.

5. Test section design

From the above discussion, it should be acknowledged that those researches of great quality like works conducted by Phani.D [15] and Youchison [16], took account of the experimental design and original data from Efremov Institute, at the same time gave similarly positive comments to it. This was a
The convective evidence for its experimental accuracy and reliability, rich of data and deft design of experiment, so the basic dimensions of test section design from Efremov Institute were the final selection for reference. Moreover, the design of the inside flow channel structure referred to the design for ITER assessment [19], because of the consideration of in/outlet flow transition, structural compactness and overall dimensions uniformity with the design of Efremov Institute.

In order to enhance high heat flux removing performance of Hypervapotron as much as possible, 2 types of auxiliary structure for the top of fins were provided (figure 4). The first fin structure is “Squeegee-shaped” top which was obtained by reforming the “Scraper” fin, and there are 3 reasons to emphasize the advantages of this new fin type: (1) provides a relatively stable velocity inside of the groove which is propitious for the appearance of the “Hypervapotron effect” (2) expands the superficial area for heat transfer (3) under the current dimensions of the overall design, for given mass flow, the corresponding flow velocity won’t have a tremendous difference. The second fin auxiliary top structure is “wave-shaped” top, whose advantages can be easily confirmed that (1) expansion for the heat transfer surface area (2) structural simplicity for processing (3) easy to maintain.

![Figure 4. Squeegee-shaped (a) and wave-shaped (b) fin](image)

Both of the presented auxiliary fin top structures have a common characteristic, which is an expended heat transfer area. To further improve the heat transfer performance and the CHF value while the subcooled boiling happens, the micro-surface processing technology will be used, which also has a positive impact on the physical properties of the surface material. At the same time, with the existence of the expended heat transfer area, the influence of micro-surface processing on heat transfer efficiency will extend.

6. Simulation analysis and drawing
Next, the flow simulation analysis (figure 5,6) was carried out with the mass flow of 0.2 kg s⁻¹, inlet temperature of 70 °C and Intel pressure of 2 MPa. Moreover, the impact of gravity of -9.81 m s⁻² was taken into concern.

![Figure 5. Inside flow channel (a) and flow velocity field (b)](image)
After the analysis with the help of Solidworks flow simulation, the preparation for manufacturing the tested Hypervapotron was illustrated down below. AutoCAD (figure 7,8) was used to design the test section, and all the needed dimensions and tolerances were labelled on the drawing sheet.

The auxiliary fin top structure was not concluded in the current AutoCAD drawing, because the operation method, processing difficulty using the micro-surface processing technology should be taken concern to when the actual processing will be carried out. The more detailed design for this part will be demonstrated in future works.

With reference to table 1, the flow parameters of the coming heat transfer experiments using the designed test section are as follows: flow velocity of 1-4 m s$^{-1}$, inlet temperature of 50-110 °C, working pressure of 1-3 MPa. The heat transfer experiment will be performed in the department of General Physics and Nucleosynthesis, MPEI.
7. Conclusion and future work
At the basis of the scientific work in the last semester, the heat transfer experimental results with the respect to the critical heat flux (CHF) from all the referred research works were analyzed thoroughly, including the different test section designs and flow parameters setting.

With the help of the data from the previous research works, graphics and table especially for the CHF experimental analyze were drawn. By comparing the details of the experiment setting, the number of citations, and completeness, the accuracy of the data, the experiment design from the Efremov Institute was selected as the best one.

In order to further improve the heat transfer process during the boiling happen and the CHF value, the test section should be one more time optimized. Two different types of the fin top structure were presented: the “Squeegee-shaped” and the “wave-shaped” fin tops. Their common characteristics are (1) expansion for the heat transfer surface and (2) that they don’t have a huge impact on changing the main flow velocity compared with the original design.

Moreover, the Flow simulation by Solidworks was conducted, which can clearly demonstrate what happens inside of the test section qualitatively and quantitatively. A drawing by AutoCAD based on the design of the Efremov Institute was also presented, which will be used for the processing of the test section. At the end of the work, experimental parameters were also explained.

In future work, the experiment results will be discussed. At the same time, the influence of the micro-surface processing on the CHF enhancement and the air-water cooling mechanism will also be taken into concern.

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