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Results of Experiment of Cooling the High Heat Fluxes Using the Hypervapotron

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Reactor cooling is a critical process in all nuclear facilities. A specific problem is the cooling of fusion reactors that are in preparation. The present paper describes an experiment to investigate the process of cooling using the hypervapotron device envisaged in fusion reactors. The aim of the experiment is to contribute to determination of correct requirements, limits and conditions for the construction of refrigeration equipment, which is planned to use in praxis. This can be only reached if experiment results are correct. The paper shows tool for regular inspections of measuring equipment and other accessories with aim to prevent the occurrence of unacceptable risks which can influence experiment results. Because measuring process is linear, we use checklists. At the end, the critical items for hypervapotron design are given.

Keywords: Cooling, hypervapotron, subcooled boiling, experiment, risk sources, safety, checklist.

1. Introduction

Nuclear technologies are associated with physical processes that lead either to the fission of heavy atomic nuclei when they collide with other nuclei or particles or to the fusion of atomic nuclei of lighter elements into the nuclei of heavier elements (nuclear fusion). During both processes, huge amounts of energy are released, which, if not controlled, can damage both, the technical equipment in which the process takes place and its surroundings. Therefore, it is necessary to ensure process safety management, in which the cooling process plays an important role. Reactor cooling is a critical process in all nuclear facilities. The present problem is the safe cooling of fusion reactors, which are under preparation.

The submitted article describes experiments by which it is investigated the cooling process using a heat exchanger with the geometry of the hypervapotron, with which it is reckoned at fusion reactors. At measurement it is used a special connection of components that have certain safety limits. To ensure the correct results, on which the risk-based design of the hypervapotron device can be based, it is necessary that the experiments are carried out with high quality and that their results are conclusive.

According to present knowledge and requirements (EU 1992), a measurement process quality needs to have main feature the safety, which guarantees both, the correct results and the protection of the lives and health of present humans, property and the working environment. Primal measurements on the experi-menttal loop using the hypervapotron device revealed that the temperature of the thermocouples in the hypervapotron wall does not decrease with increasing the coolant flow as it was expected. This fact indicates that the cooling performance or the temperature on the thermocouples is unstable under otherwise constant conditions and even undergo sudden changes.

To reach correct results, we have started regular checks of the measuring equipment and other accessories as well as the measurement process using the checklists with aim to prevent the occurrence of unacceptable risks that cause large changes in the cooling trend. Their application revealed that the temperatures measured in the hypervapotron wall are significantly affected by changes in the structure of the material from which the seal around the hypervapotron sample is made. As a result of this problem, water leaks and steam forms in the measuring area, which adversely affects the temperatures on the thermocouples. These phenomena occur from a certain level of coolant flow due to exceeding the seal resistance limit. Therefore, from safety reasons, we propose measures for removing this problem.

2. Summary of Knowledge on Cooling the Fusion Reactors and Hypervapotron

A fusion reactor consists of many parts and each has slightly different demands in terms of materials, heat flow, etc. Heat flux refers to the heat that passes through a certain area per unit of time. Therefore, when controlling the technology, there is a problem of cooling the component parts (Chang, Baek 2003). One of the heat-stressed systems is, for example, the Neutral Beam Injector system, in which a hypervapotron is used to dissipate heat fluxes up to 30 MW/m2 in the JET tokamak (Pitonak 2016). This system is used to heat the plasma and its output can reach about 100 MW (Falter, Thompson 1996).

In divertor regions, the heat flux reaches values of up to 20 MW/m^2 and may increase with time (Pitonak 2016). One possible candidate for widespread use is the hypervapotron (Pitonak 2016), shown in Figure 1. It is a cooling device in the shape of a canal, which is equipped from the inside with fins measuring in the order of millimeters. In the channel in the spaces between the ribs, the incoming water evaporates and the resulting steam condenses. The device in question uses supercooled boiling, when the mean temperature of the coolant in the channel is far below the saturation temperature. Heat transfer is highly dependent on flow parameters, working medium, hypothermia temperature and channel geometry. At present, the maximum heat flux is up to 30 MW/m^2. Due to the high velocities inside the channel and the presence of ribs that are located perpendicular to the direction of the coolant flow, the large turbulence makes it easier to detach bubbles from the surface and thus improve heat dissipation.

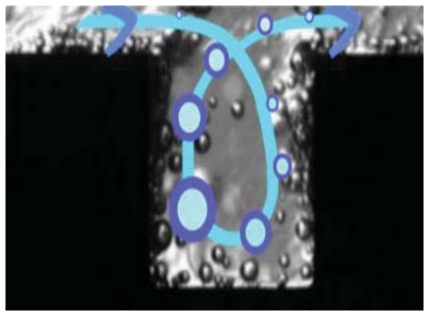

Fig. 1. Hypervapotron equipment; taken from (Chang, Baek 2003).

Because of the high requirements for heat dissipation, the hypervapotron must be made of a material with high thermal conductivity. According to the work (Pitonak 2016), the only applicable option for fusion reactors appears to be CuCrZr material, which, in addition to high thermal conductivity, also excels in good radiation resistance and high strength. A diagram of the hypervapotron used in the JET tokamak in Oxforshire (Miles 2010) is shown in Figure 2.

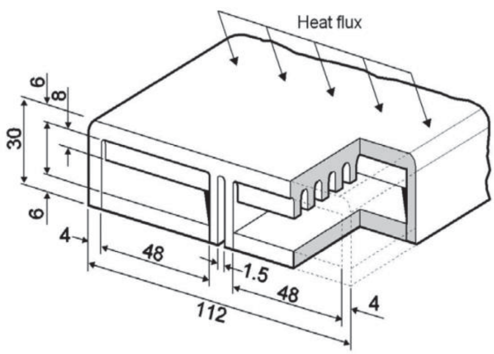

Fig. 2. Scheme of hypervapotron; processed according to (Pitonak 2016).

3. Risks and Safety of Experiments

If we want to solve a problem, we must first know and understand it, which can only be done by: knowledge, which is based on the collection of data by observation and experimentation, and on the formulation and testing of hypotheses; and applications of correct methods, i.e. methods that are repeatable, transparent, have clearly defined quantities, units and terminology (Prochazkova, Prochazka 2015). In order to gain knowledge by measurement, we need a high-quality method of measuring the data from experiments that are processed by a suitable mathematical method. For the data obtained to be credible, the measurement process must be as follows: sufficiently flexible; transparent; repeatable; accurate in the sense that it produces the same results when repeated; and correct in the sense that both types of uncertainty, random and knowledge, are evaluated (Prochazkova, Prochazka 2015). According the cited publication, measurement errors are divided into: systematic (continuous); gross; and random.

Systematic errors are errors that occur during the experiment throughout the measurement and deflect the measured values in the same direction. A systematic error can be an inaccurate scale of the gauge – instead of subtracting the correct values, we read distorted values. Gross mistakes are made by the experimenter mainly by inattention or fatigue by incorrect subtraction from the scale, incorrect setting of experimental conditions, incorrect circuit wiring or selection of the wrong device. These mistakes must be avoided. Random errors are a natural part of measurement and cannot be eliminated. These errors can cause, for example, random shocks of the measuring apparatus, random air flow, random temperature fluctuations or fluctuations of the measured quantity itself. The nature of these errors is random, so it is possible to correct it with a larger number of measurements and by determining the arithmetic mean from the measured values. This is because we are equally likely to measure a greater and smaller value than the actual value of the measured quantity, so by averaging we get the best possible estimate of the measured quantity. In most cases, the measured quantities have a so-called Gaussian distribution.

Practice (Prochazkova 2018) shows that conditions, especially external ones, affect results of processes, including the measurement processes; they cause the epistemic (knowledge) errors. These errors are caused by reality that process proceeds differently. Therefore, it is necessary to monitor the conditions under which the measurement takes place, as well as the knowledge, abilities and skills of the person making the measurement. It means that for high-quality measurement results, it is necessary to have a safe measuring instrument, a safe measurement procedure and the ability to perform measurements in a safe environment.

4. Description of Experiment and Its Results

The laboratory is located in the hall laboratories of the Department of Power Engineering of the Faculty of Mechanical Engineering of the Czech Technical University in Prague, at Technicka 4 (Gleitz 2022). Its location is situated under the landing on the ground floor. Illumination of the room is provided by a roof skylight and a set of fluorescent lighting. Heating is provided by steam radiators in the ceiling part above the landing and steam radiator on the opposite side of the room. Cooling in the room is not provided. Air exhaust is provided by ceiling fans. The air supply is provided by the joints of the door and other leaks of the room. The water supply from the water system is provided by a system of taps on the ground floor next to the steam radiator, water drainage is provided by a system of channels in the floor. The power supply is provided by a number of electrical cabinets in different parts of the laboratory. Below the laboratory there are other laboratories of the Institute of Electric Drives and Control.

The laboratory is equipped with measuring equipment, equipped with a source of electricity, a water source, a bottom drain, furniture, a control computer and other components that are needed for conducting experiments. The water experimental loop is shown in Figure 3.

The maximum loop operating parameters are listed in Table 1. The process model of the experiment investigating the cooling process using the hypervapotron device is shown in Figure 4. The model consists of three circuits, which are distinguished by color in the Figure 4.

The measuring circuit (shown in red in Figure 4) consists of hydraulic devices which are connected to each other by copper piping. It is further rated at 10 bar and 110 °C at maximum. The M1 pump is equipped with a frequency converter that allows a continuous change of flow from approx. 2 to 416 l/min stably. The pump is also equipped with a bypass, which is controlled by means of a ball valve. The pump is also connected to the M2 electric heater, which is used to induce and maintain a constant temperature at the entrance to the measuring area. Then the circuit continues through the induction flow meter M3, behind the knee from the flowmeter is a T-piece parallel connected expansion tank and safety valve set at 10 bars, these devices are not included in the scheme. The T piece is followed by the M4 measuring area itself. It begins with pressure and temperature measurement with a PT100 thermometer placed in a stream of water, followed by a channel used to transition from the circular cross-section to the cross-section of the hypervapotron geometry and also to attach the hypervapotron sample itself.

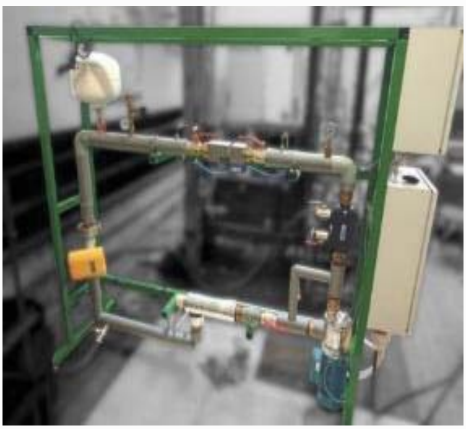

Fig. 3. View of the water experimental loop.

Table 1. Maximum loop operating parameters.

Parameter	Value
Maximum pressure	<10 bar
Maximum flow	416 l/min
Maximum flow velocity	19 m/s
Maximum water temperature	<110 °C
Maximum performance	15 kW
Maximum heat flow	12 MW/m^2

The measured sample of the hypervapotron is fixed by means of a clamping joint through 5 mm seals. The hypervapotron, which works as a heat exchanger, is supplied with thermal energy using the electromagnetic induction I2. The measured hypervapotron sample and seal are followed by a circular cross-sectional transition, a differential pressure probe and a PT100 thermometer reading the temperature behind the channel. The measuring area is followed by the M5 cooler, the task of which is to remove excess heat from the circuit. The cooler is followed by a T-piece to bypass the M1 pump, which closes the measuring circuit. Table 2 summarizes the name and short information on each device.

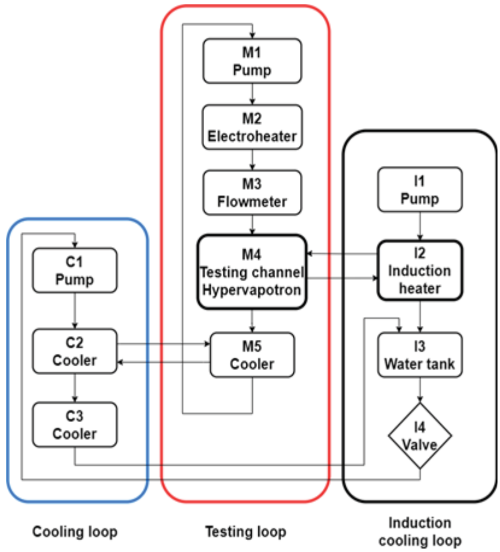

Fig. 4. A process model of an experiment that investigates the cooling process using a hypervapotron device (Gleitz 2022).

Table 2. Name and basic information of each device.

M1	Pump of measuring circuit Caleda MXH 1603 1.8 kW with frequency converter
M2	Electric heater 3 kW – pipe with heating coil 3 kW, custom production 4jtech
M3	Induction flow meter Flonet FN2010.1
M4	Measuring channel with measured sample of hypervapotron, custom production 4jtech
M5	Cooler Pahlen Hi-Flow 13kW
C1	Pump Star-RS25/4 48 W, 1x230V
C2	Cooler with fan 190 W, 3x400 V
I1	Pump Calpeda CT61 330 W, 3x400 V
I2	Induction heating USS-HFIH00001 15 kW, 1x230 V, 60 A
I3	Water reservoir 80 l
I4	Valve with T piece

The second necessary circuit (marked in black in Figure 4) is the induction cooling circuit. This is used for the safe operation of electromagnetic induction I2, which is used to generate thermal energy in the hypervapotron sample. The circuit starts with the circulating pump I1, which subsequently supplies the minimum necessary water flow through electromagnetic induction I2. Water is used to cool the components of electromagnetic induction and the coil itself, which generates an electromagnetic field in the measuring space of the M4 hypervapotron, which is subsequently converted into thermal energy in the hypervapotron sample. The I2 induction is followed by an auxiliary cooler, which, however, is used absolutely minimally and is therefore absent from the diagram in Figure 4. From the auxiliary cooler, the circuit continues to the I3 water tank, which is also shared with the cooling circuit. At the bottom of the I3 water tank there is an outlet through the I4 valve, which is equipped with a T piece, which subsequently distributes the water stream into the induction cooling circuit and the cooling circuit, thus closing the circuit.

The third circuit is the cooling circuit (marked in blue in Figure 4), which is used to remove excess thermal energy from the measuring circuit and thus stabilizes the temperature at the entrance to the measuring area of the M4 hypervapotron. The circuit starts with the C1 pump, which conducts water through the M5 cooler, which is located in the measuring circuit. From the M5 cooler, the water is led to the C2 cooler, where the excess heat from the measuring circuit is removed to the room by an air fan. From the C2 cooler, the water is led to the I3 water tank, which is shared with the induction cooling circuit. At the bottom of the water tank there is a valve that is equipped with a T-piece, which ensures that one branch drains the water back to the C1 pump. This closes the cooling circuit.

An example of the first results of the hypervapotron cooling efficiency measurement is shown in Figure 5. In this example and others, when measuring the dependence of temperature on flows, greater dispersions of measured values appeared in two places, so it is necessary to find the cause.

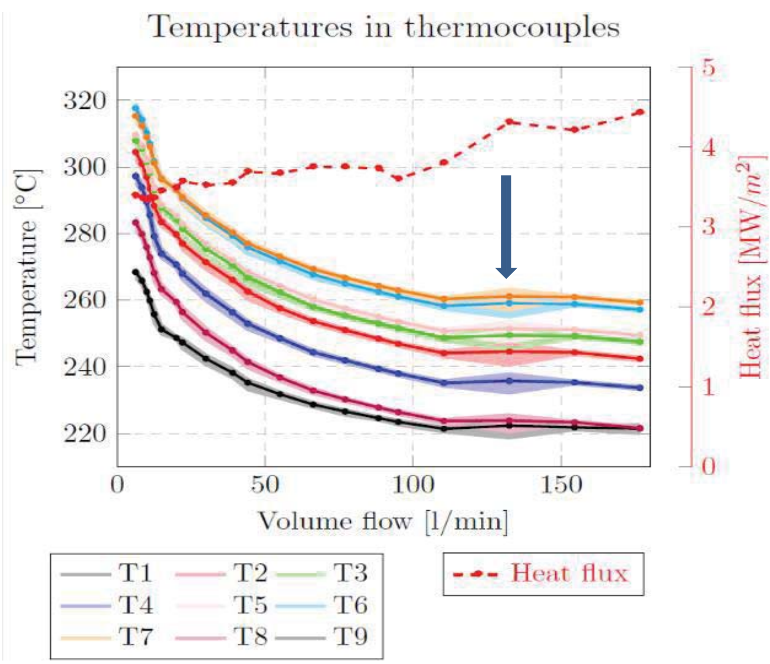

Fig. 5. The course of temperature decreases with flow (Gleitz 2022).

The causes of these dispersions have not physical explanations, and therefore, in line with the findings in Chapter 3, we started to monitor external conditions when measuring using the checklists.

5. Checklist Method

A checklist is a tool used in practice to systematically check the fulfilment of predetermined conditions and measures (Prochazkova 2018). When drawing it up, the procedure is used: specifying the items to be considered in the area to be monitored; order items based on their severity for the followed area; . identification of critical points that are a source of risk (non-compliance means serious risk); the development of checklist questions; and determining how the checklist should be evaluated.

According to the recommendations in(Prochazkova 2018), the scale in Table 3 is used to evaluate a simple checklist (evaluation – YES if the answer to the question is yes; otherwise it is NO).

Table 3. Value scale for determining the level of risk in measurement; the risk level $r = n/N$, where n is the number of answers NO and N is the total number of questions.

Risk rate	**Values *r in* %**
Extremely high – 5	More than 95 %
Very high – 4	70 - 95 %
High – 3	45 - 70 %
Medium – 2	25 – 45 %
Low – 1	5 – 25 %
Negligible – 0	Low than 5 %

6. Checklists for Knowledge-Based Experiments Cooling Process for High Heat Fluxes

Laboratory conditions inspection shall be carried out upon entry to the laboratory according to the checklist in Table 4.

Table 4. Checklist for assessing conditions in the laboratory; Y-YES, N - NO.

Item to be checked	**Y**	**N**
Is electricity supply ensured?		
Does the layout of the equipment in the laboratory correspond to the requirements for laboratory operation?		
Is water supply ensured?		
Is the bottom drain a serviceable?		
Are the meteorological conditions in the laboratory normal?		
Is the control computer operational?		
Is the frequency inverter set up well?		
Does the flow meter work?		
Are there open valves on the cooler?		
Is the cooling circulation pump switched on?		
Is the pump power set sufficiently?		
Are the hoses watered?		
Is the water in the water tank cool enough?		
Are the valves open?		
Is the pump working?		
Is cooling working?		
Is induction heating functional?		
Is the flow meter powered by 1x230V?		
Are all valves open?		
Is the electric heater powered through the 3x400 cabinet?		
Is the person taking the measurements trained?		
Does the person who performs the measurements know the regulations of OSH and the technical standards for working with equipment components?		
Total		

In case of critical faults such as: no electricity is supplied to the laboratory; malfunctioning pump; insufficient pump power; malfunctioning flow meter; unopened valves; watered hoses; too high temperature in the water tank; unconnected induction heating, it is necessary to remedy the defects in question before the measurement, i.e. to introduce acceptable conditions for the course of the experiment.

A positive result of the laboratory conditions inspection shall be followed by an inspection of the measuring equipment according to the checklist in Table 5. In the case of critical defects, it is again necessary to remove the defects before the measurement, i.e. to introduce acceptable conditions for the course of the experiment.

It is important to carry out the inspection even after the measurement is completed, because:

- Various hoses connected to the taps to supply water for further experiments and their fail-

Table 5. Checklist for assessing the conditions of the measuring equipment; Y-YES, N - NO.

Item to be checked	Y	N
Measuring loop conditions		
Are all the valves of the measuring loop open?		
Is the loop filled with water at the required pressure?		
Are the water supply and outlet valves closed?		
Is the loop power box plugged into a power source?		
Is the flowmeter connected to a power source?		
Cooling water supply conditions for loop and induction heating		
Is there enough cool water in the tank?		
Is the valve on the tank outlet open?		
Induction heating loop conditions		
Is the valve behind the circulating pump of the induction heating loop open?		
Is the circulating pump of the induction heating loop plugged into a power source and gives a sound response that it is running?		
Is the induction heating connected to the power source?		
Is the induction heating switched on (circuit breakers + power button)?		
Is the cooling loop put into working condition?		
Are the inlet and outlet valves on the measuring loop radiator open?		
Is the circulating pump of the cooling loop connected to the power source?		
Is the cooler fan of the cooling loop plugged into a power source?		
Is the loop control working?		
Is the RJ45 communication cable connected to the power loop of the measuring loop and the control computer?		
Is the computer with the control tool turned on?		
Are all measured values within a realistic range?		
Condition of pipe and hose connections		
Is there a tight measuring space with a hypervapotron sample?		
Is the threaded connection tight in front of and behind the measuring area?		
Are the remaining joints tight?		
Total		

ures to close can cause over pressurization and uncontrolled leakage from the water mains.

- The critical point is then the degree of tightening of the sealing clips. Leakage can cause wetting of various devices, which may begin to corrode, or in the case of electrical equipment even conduct electric current, which may lead to the risk of electric shock to people, further waterlogged masonry, or the floor can drain to other laboratories, where they can cause further damages.
- Failure to disconnect equipment from power sources may lead to an increased risk of accidents related to leakage of electricity in connection with the above leaks.
- Clutter in the lab can lead to injuries or damage to expensive equipment.

The inspection of the measuring equipment after completion of the measurement is carried out according to the checklist in Table 6.

Table 6. Checklist for assessing the compliance with the conditions for shut-down of measuring equipment; Y-YES, N - NO.

Item to be checked	Y	N
Is the induction heating inactive, i.e. does not give a sound response?		
Is the measuring loop pump switched off?		
Is the electric heater switched off, does it not deliver power and temperatures do not rise?		
Is the cooling circuit circulation pump switched off?		
Is the circulation pump of the induction heating circuit switched off?		
Are all electrical appliances disconnected?		
Is the power supply of the measuring loop disconnected?		
Is the induction heating power supply disconnected?		
Is the cooling circuit circulation pump power disconnected?		
Is the induction heating circulation pump power supply disconnected?		
Is the cooler power of the cooling circuit disconnected?		
Is the auxiliary induction heating cooler disconnected?		
Is the flow meter power disconnected?		
Is the measuring loop drain valve open?		

Table 6 (continued)

Is the valve closed behind the induction circuit circulation pump?
Are the valves on the inlet and outlet to the cooler of the measuring loop closed?
Is the exhaust valve from the water tank closed?
Is the measuring loop drain valve closed?
Are changes visible on the hypervapotron?
Is there damage to the seals around the hypervapotron device?
Total

7. Conclusion

In order to achieve quality results of experiment, we have step by step improved the working procedures of experiments and the training of experimental equipment operators. By the application of checklists and detailed monitoring of the surroundings of the experimental device during the measurement we revealed that under certain conditions (precisely where in Figure 5 there is either a jump or a large dispersion of values) steam escapes around the hypervapotron, because significant damage to the seals around the hypervapotron during the measurement. It means that material of seals around the hypervapotron is critical item, which must be considered in the hypervapotron design.

Based on this, we began to take great care to insert the gasket around the hypervapotron before measuring, and we placed an umbrella above the hypervapotron so that the escaping steam could not affect other components of the loop. There was an improvement in the results.

By detail analysis of technical aspects given in checklists, we also found that outside the operating conditions, the great influence on sealing the components has also quality of contact surfaces of components to be joined. The last surface treatment of the surface that is part of the experimental channel is milling. The final treatment of the seal surface is grinding. Since the surfaces are not perfectly straight and smooth, silicone sealant is applied between the seal and the component to compensate for unevenness. This silicone sealant with a maximum operating temperature of 300 ° C (in the given area the performance temperatures are above 400 ° C) is therefore the biggest weakness, and therefore it is necessary to remove it from the system.

This can only be achieved by improving the quality of sealing surfaces of the seal/component interface and maintaining optimal tightening, or by redesigning the component. Therefore, we will check the sealing surfaces in future experiments by non-destructive tests, such as:

- Visual test.
- Roughness measurement.
- Leak test, etc.

We will then assess the test conclusions in terms of safety and reliability in order to achieve quality results.

Experiments are being performed on small sample of hypervapotron. Further problems of hypervapotron design will be necessary to solve when the complete system of hypervapotron parts will be interconnected.

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