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Advanced design of the Mechanical Tritium Pumping System for JET DTE2

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For tritium processing in JET during the next Deuterium-Tritium-Experiment (DTE2), a fully tritium compatible and continuously working vacuum pumping system has been developed. This pump train will be used to cover a pressure regime between 10^{-1} Pa and ambient pressure. Therefore, a two-stage liquid ring pump in combination with a booster pump will be applied.

In this paper, a close-to-final design of the pumps is being described. Finite element (FEM) simulation results of components where high mechanical stresses due to thermal gradients are expected are presented. Furthermore, the final design of the control and data acquisition system is shown and explained.

Keywords: DEMO, vacuum, tritium, liquid ring pump, mercury, FEM analyses

1. Introduction

The conceptual design of the Mechanical Tritium Pumping System (MTPS) has already been described in an earlier paper [1]. The present paper completes the design work and gives further details. Now, the MTPS layout planning, the design development of the vacuum pumps and other major components (e.g. baffles for mercury hold-back) is finalized and component manufacturing and MTPS set-up has been started.

Heart of MTPS is a two-stage liquid ring pump (LRP) that has been modified in collaboration with industry towards mercury as working fluid. This modification was necessary as mercury is the only available working fluid that can be used in the pumps [2], mainly due to its perfect tritium compatibility [3] and its extremely low solubility for tritium [4]. In addition to the LRPs, a booster pump that is expected to extend the operational pressure regime towards lower inlet pressures (10^{-1} Pa region) shall be integrated. Also here, a commercially available (oil-) booster pump has been used as starting point and was modified towards mercury as working fluid. This booster pump will be integrated in the pump train only if positive test results of the modified pump allow for this. This paper is based on the assumption that this can be done.

2. MTPS design description

2.1 Pump train layout

All pumps are installed in an airtight housing (enclosure) that is kept at an underpressure of up to 1000 Pa. The enclosure is monitored for fire, high activity, mercury- and water leaks. Directly beside the housing are three cubicles for power supply and the control system and one cubicle for the infrastructure systems (cool water-, gas- and nitrogen supply). Altogether, this leads to an overall dimension of the MTPS unit of 3.3 m length x 1.6 m width x 2.4 m height with a total mass of approx. 2.5 tons. Fig. 1 illustrates the final arrangement of the hardware inside the enclosure.

To avoid mercury propagation towards outside MTPS, an inlet baffle (2) and an outlet baffle (7) will be installed. Here, mercury is being removed by cooling using two-stage cold traps. The baffles are supplied by cold nitrogen gas for cooling, obtained by evaporation and heating of liquid nitrogen [1]. The connection to the Active Gas Handling System (AGHS) at JET is done via a DN63CF inlet- (1) and a DN40CF outlet (8) flange. Downstream the inlet baffle, the booster pump (3) is located. This pump works like a diffusion pump and needs a mercury boiler (4) for the supply with gaseous mercury right below the pump. Downstream the booster, two LRPs (5, 6) are connected in series to form a two-stage LRP. This pumping system will provide an inlet pressure low enough to operate the booster pump (100 Pa region).

** See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

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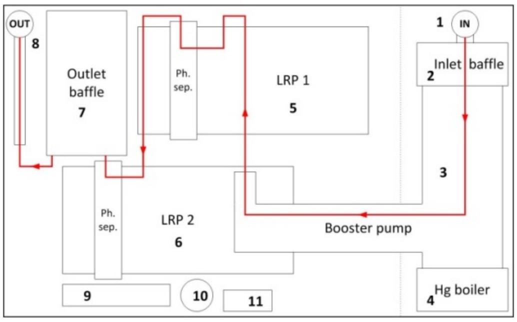

Fig. 1. Arrangement of the pumps and components inside the enclosure (side view).

Downstream the outlet baffle, the gas is cold (200 K) and has to be heated up to ambient temperature before reaching the outlet valve (8). This is done using an electric exhaust gas heater comprising three parallel 25 mm pipes with a length of ~1000 mm each, heated from outside via glass fiber heating wires (Hillesheim Type HS) with 6 m length and 0.8 kW heating power each. To avoid overheating, a safety temperature transducer (Phoenix Contact Type MCR) will be installed.

The whole mercury in the pump train (~30 liters or 400 kg) can be drained into a blowdown vessel (219 mm diameter; 10) which marks the deepest point of the system. The mercury level in the vessel is measured by a magnetostrictive level meter with an all-metal floater adjusted for the density of mercury (Wika Type FLM). It can be pumped back to the system via a mercury gear pump (Gather Type 2M-K; 11) and a set of 10 mm pipes and pneumatic all-metal bellow-type valves (Swagelok, Type 4BW-V51-5CM). All pipes and valves are connected using Swagelok VCR connections (with stainless steel sealing) or orbital welding.

2.2 Liquid ring pump

In 2015, a liquid ring pump design (Fig. 2) has been developed together with an industrial partner (Hermetic GmbH Gundelfingen, Germany). Liquid ring pumps are reciprocation positive displacement pumps in which a liquid ring acts as a liquid piston [5].

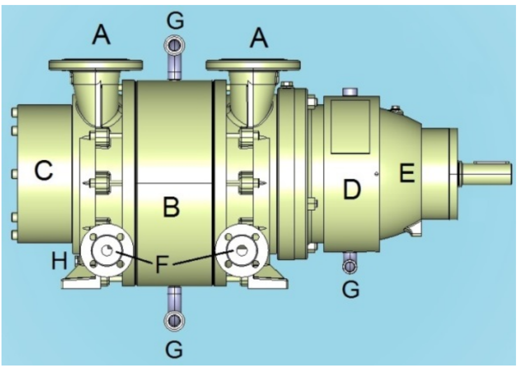

Fig. 2. CAD design of the liquid ring pump.

To fulfil the requirements to the ring pumps described in [1], the following major modifications have been implemented:

- Replace all polymer seals against metal seals with pure iron coating (Armco by Helicoflex) or graphite seals (only in one exceptional case where the high clamp force for the Helicoflex seal cannot be provided); modify the flanges suitable for all-metal seals (A, F).
- Avoid polymers on the internal control disc. This means that the maximum pumping speed is reduced in benefit of a low ultimate pressure.
- Implement ceramic bearings (CEROBAR, silicon nitride bearings with V4A cage; C, E) and magnetic coupling (E) to make it hermetically tight (target leak rate: < 10^{-9} mbar l/s).
- Include cooling jackets (B, D) for pump housing and magnetic coupling (E). Include ¾" cool water connections (G).
- Include a drain connection (H) for pump filling and draining and a fore-separation connection (F) for mercury.

The overall weight of one pump is ~370 kg. The outer dimensions are (l x w x h) 850 mm x 520 mm x 450 mm. We expect a pumping speed of some ten m^3/h at an inlet pressure of few mbar; exact values will become available after MTPS testing in the THESEUS test facility at KIT [2].

The working fluid volume is expected to be ~10 liter per pump. For pump propulsion, a 7.5 kW gear engine (SEW Eurodrive Type RX97 DRE132) controlled by a Variable Speed Drives (VSD) will be installed. The expected power consumption during operation will be ~4 kW. As no access to the pumps is possible during operation, a vibration sensor (GE Bentley Nevada Type 177230) will be installed close to the drive-end of each pump to detect potential bearing failures.

2.3 Booster pump

To bridge the pressure gap between the torus vacuum system at JET and the LRPs, a mercury booster pump is foreseen. As mentioned earlier, a commercially available booster pump (EDWARDS 14B4B) has to be modified for mercury as working fluid and to make it fully tritium compatible (Fig. 3). This asks for:

- A redesign of the mercury boiler (3) for 50g/s mercury, with an increased heating power and optimized volume that is resistant to hot (160°C) mercury by enameling it.
- The replacement of the pump casing (4) by components that allow 100% radiography and a stronger cooling (necessary due to the increased pump heating power).
- The modification of the connection flanges (1, 5) towards CF flanges that allow the use of metal seals that require higher forces

The internal nozzles (2) as heart of the pump will be re-used from the original pump. It must be noted that all internal dimensions are kept constant in order not to change the functional design.

For the modification of the pump towards mercury, the boiler re-design was made such that for both operating fluids, the same total cross section of molecules is needed to keep the performance constant for both. This leads to the assumption that approx. 2.5 times more heating power is needed. For practicality reasons, 13 kW have been installed finally.

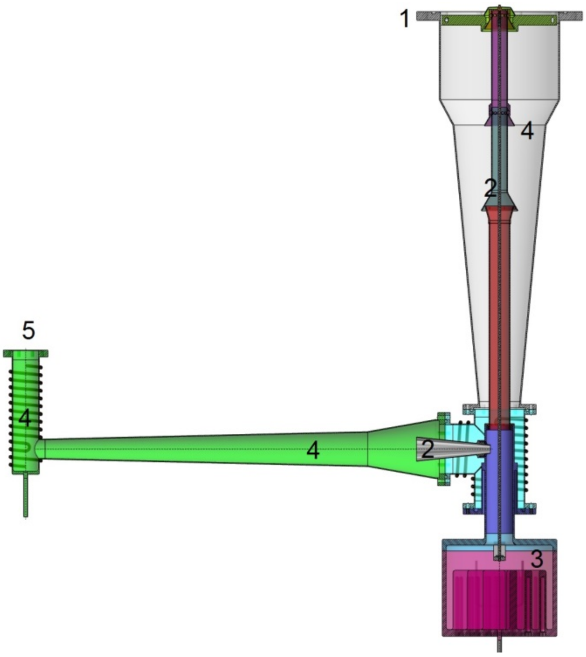

Fig. 3. Drawing of the booster pump. (1= Inlet, 2=Nozzle stock, 3=Mercury boiler, 4=Pump case with surface cooling, 5=Outlet)

3. FEM simulation results

3.1 Inlet baffle

The inlet baffle comprises two baffle stages, an upper one at a temperature of 200 K and a lower stage at cool water temperature 270 K [1]. The housing is considered as adiabatic (insulated). After meshing (the model comprises more than 2 Mio. hexagonal and tetragonal elements), the resulting temperature distribution has been calculated as shown in Fig. 4. For all work done in this paper, we have used ANSYS for simulations.

Based on the temperature distribution, the mechanical stresses have been calculated in different parts of the baffle separately, using a finer mesh (casing, baffles, main flange and shielding plate) for higher accuracy. The simulation results are summarized in Table 1. The safety factor – i.e. the limit stress value over the max. stress as calculated in the simulation – is in all cases higher than 1.

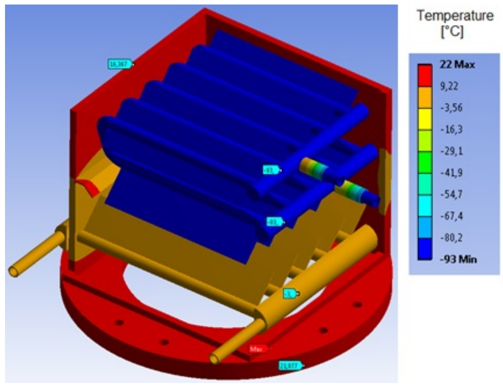

Fig. 4. Temperature distribution on the inlet baffle.

Table 1. Results of the FEM analyses for the inlet baffle.

Part	Max. stress	Limit [6]	Safety factor
Casing	96.2 MPa	220 MPa	2.2
Baffles	104 MPa	220 MPa	2.1
Main flange	119 MPa	220 MPa	1.8
Shielding plate	137 MPa	220 MPa	1.6

3.2 Outlet baffle

The outlet baffle comprises again two stages: A vertical pipe with cooling jacket as pre-cooler (Fig. 6; where the gas is slowly cooled down at 240 K and in which most of the mercury is condensed out) and a plate heat exchanger (Fig. 7) in which the residual mercury is removed by freezing at 200 K. The cooling gas (nitrogen) enters the plate heat exchanger, passes it in a counter-current flow and is finally used for cooling the pre-cooler. To keep the temperature in the pre-cooler at constantly 240 K, the inner pipe is heated electrically using a stainless steel heating wire, controlled by a power controller (JUMO Type TYA 201). All pipes are connected from below to the 300 mm bottom flange using Helicoflex seals. For insulation, a vacuum vessel that acts also as a safety barrier is being placed above the pipes and the heat exchanger equipment.

A simulation as already done for the inlet baffle has been performed assuming the temperatures as explained above. The insulation vacuum vessel as well as the bottom flange is assumed to be insulated again. The resulting mechanical stresses for the pre-cooler, the plate heat-exchanger and the bottom flange are shown in Fig. 5, Fig. 6 and Fig. 7, respectively.

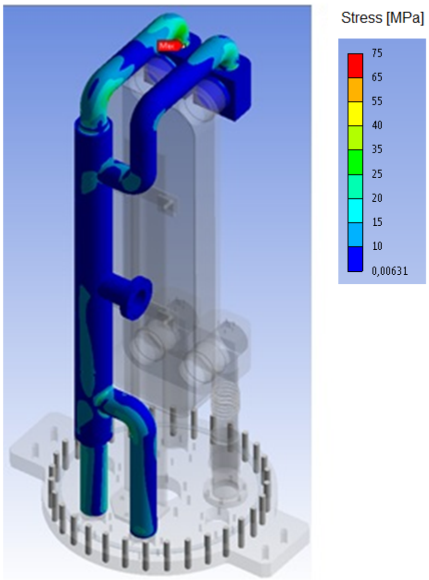

Fig. 5. Stress values in the pre-cooler.

As result of the simulation, two modifications had to be done on the design: Firstly, a bellow has to be inserted in the cold nitrogen supply pipe (see Fig. 6) to reduce stresses. Secondly, the bottom flange must be connected to the support structure via rubber compensators; a complete fixing to the structure would lead to intolerable high stresses. Table 2 summarizes the results of the FEM analyses. It can be seen that the safety factor for all parts of the outlet baffle is much higher than 1.

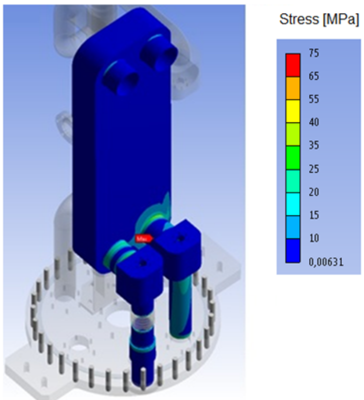

Fig. 6. Stress values in the plate heat exchanger.

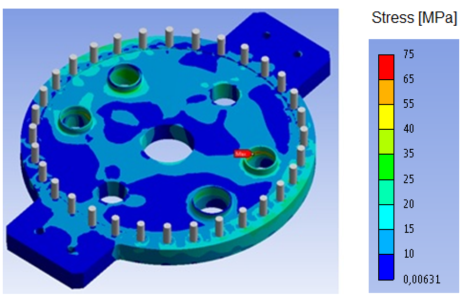

Fig. 7. Stress values in the bottom flange.

Table 2. Results of the FEM analyses for the outlet baffle.

Part	Max. stress	Limit [6]	Safety factor
Vacuum vessel	48 MPa	220 MPa	4.5
Plate heat exchanger	69 MPa	220 MPa	3.2
Pre-cooler	74 MPa	220 MPa	2.9
bottom flange	72 MPa	220 MPa	3

3.3 Mercury boiler

As already discussed in chapter 2.3, it was decided for practical reasons to install 13 kW of heating power, controlled by three power controllers (JUMO Type TYA 201). This gives the option to investigate the effect of heating power variations on the pump performance. Originally, it was planned to use six heater cartridges (3 kW each) installed in two circular and concentrical heating pins milled out of a stainless steel block (to avoid seams that cannot be checked by radiography). Simulation results have shown for this case that the stress values in the boiler are much too high because of the asymmetric temperature distribution in the pins.

In an iterative process, a solution has been developed that is based on a boiler (295 mm diameter) with three circular heating pins, heated by 42 heater cartridges (310 W each). Due to its symmetry, simulations have been done only for 120° sections (Fig. 8) with 0.94 Mio. hexagonal and tetragonal elements each. As result of the stress analyses, a safety factor of 1.14 has been found for this solution.

In each of the three sections shown in Fig. 8, 14 heater cartridges are screwed into the heating pins from below. They can be changed without opening the boiler.

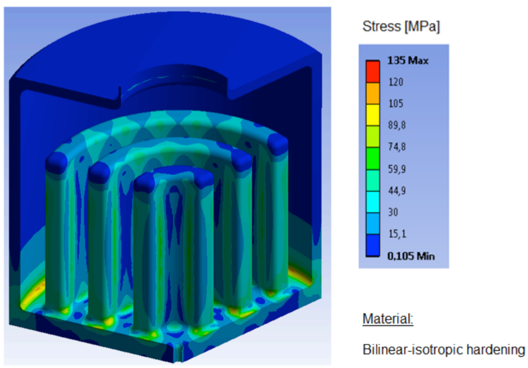

Fig. 8. Stress values in the boiler during operation.

Also the temperature on the pins has been simulated (Fig. 9) to ensure that the maximum allowed temperatures in the heater cartridges and the pins (200°C) are not exceeded. If these temperatures are exceeded, the limiting stress values mentioned below are not valid anymore and the Leidenfrost-effect may occur (at heat fluxes >100 kW/m²) what would lead to a strong decrease in heat transfer to the boiling mercury. Every second heater is temperature surveyed (alarm value: 220°C) by thermocouples Type K.

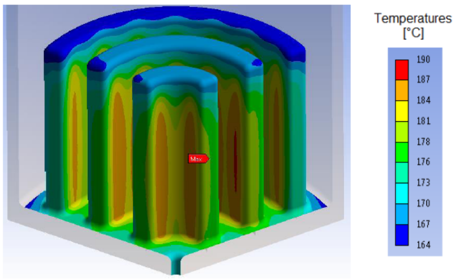

Fig. 9. Temperature distribution on the heater pins.

Table 3. Results of the FEM analyses for the outlet baffle.

Part	Max. stress	Limit [6]	Safety factor
Mercury boiler	135 MPa	167 MPa	1.24

4. The MTPS control and data acquisition system

The whole system can be controlled remotely from either a local control panel or via a dedicated workstation in the AGHS control room. The Programmable Logic Controller (PLC; Siemens S7-1515F-2PN) is equipped with two ProfiNet ports and one ProfiBus communication processor. The ProfiNet connects the two input/output (IO) devices and the workstation in the AGHS control room with the PLC using TCP/IP protocol. The ProfiBus connects heater controller for MTPS bake-out (PMA Type KS Vario), the valve cluster (Festo CLX), the gateway for the VSDs (by SEW Eurodrive), the power meter for the main supply line (Janitza UMG96) and the Siemens panel-PC for local control with the PLC. The FieldPG for PLC programming will be connected directly to the PLC via ProfiNet. Programming is done using the Siemens TIA portal. The entire control system is supplied by 24V DC, provided by a redundant 20A power supply. This guarantees even in case of a power failure the full functionality of the system including all measuring devices and alarm functions.

Independent from the main control system (only the fail-safe 1515F processor is shared) described above, there will be safety system based on fail-safe modules (directly attached to the 1515F processor) to avoid mercury mitigation by monitoring (i) the temperatures on the baffles and (ii) the pressure gradients over inlet- and outlet valves. The pump train can only be connected to the JET vacuum systems if the temperature on the baffles is low enough (< 200 K) and the pressure inside MTPS is lower than outside for the inlet valve and higher than outside for the outlet valve. If these requirements are not fulfilled, a bypass valve is opened and the inlet- and outlet valves disconnect MTPS from JET immediately. This safety system controls the three valves via additional pressurized air valves located in the pneumatic hoses between valve cluster and inlet-, outlet- and bypass valve, respectively. This ensures that the function is independent of the bus system or the valve cluster.

In addition to the PLC based systems, a hard-wired system will be installed for safety reasons. This monitors the MTPS enclosure for fire and water-, mercury-, hydrogen- and tritium leaks. If this system trips, MTPS goes into bypass operation as described before and all heaters and pumps are switched off by relays. Water leaks are detected by an optical level switch (Wika Type LSO) on the lowest point of the enclosure.

On this position, also the resistance between two thin (1 mm) wires (0.5 mm distance) is measured to detect mercury leaks. The two wires are embedded into a glass-fiber insulator and shortcuted by a 0.8 kΩ resistor. The resistance is measured by a Phoenix Contact Type MCR device with alarm values of >1 kΩ (wire break) and <0.5 kΩ (mercury leak).

For hydrogen leak detection, a hydrogen sensor (Dräger Polytron 7000) will be installed and gives an alarm if 25% of the lower explosion limit is exceeded. Activity monitoring to detect tritium leaks is done using an open ionization chamber (Premium Analyse Type MLB with IONIX 2 controller) that is set to an alarm value of 50 MBq. As fire detector, an ABUS optical smoke detector (Type RM1000) is used. The whole hard-wired system is realized by the cascaded arrangement of Siemens 3SK1 safety relays. The status of the system is indicated by LED lamps located at the front side of the cubicles. If the hard-wired system has tripped due to one reason described above, or if the emergency stop button has been pushed or if the 'remote enable'-contact has been removed, MTPS can only be restarted again after the problem is solved and a reset action is done using a key lock on site.

For local control, a panel-PC (Siemens IPC477D) has been chosen instead of a simple touch-panel because the set-up software for the VSDs, the PMA heater controller, the JUMO power controllers, the Phoenix Contact temperature transducer and the Janitza power meter run on this computer. As human machine interface (HMI), the Siemens WinCC software is used on the PC. The main pump control screen is shown in Fig. 10. The inlet-, outlet- and the bypass valves can be seen clearly in the upper part. The booster pump and the two liquid ring pumps are shown below. Details on the baffle-, cool water-, power-, mercury- and bake-out system are shown on other screens, as well as the enclosure monitoring and the status of the safety and interlocks.

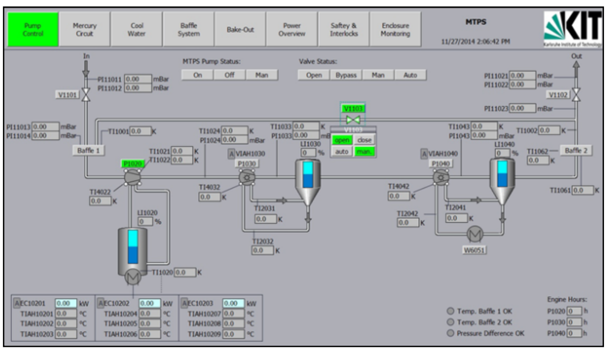

Fig. 10. Main control screen of the Siemens panel-PC.

The WinCC software allows recording and export of some measurement values. In particular, the pressure values obtained by 7 MKS Type 902B piezo gauges (pressure range: 0.1 to 1000 Torr), 3 MKS Baratron Type 626 gauges (pressure range: 1 to 10^{-4} Torr) and a number of temperature values (Pt100s and thermocouples) are recorded. Including the infrastructure systems (cool water, cold nitrogen supply etc.), a total number of 96 temperature values and 32 other analogue inputs are transmitted to the PLC system and displayed on the HMI screens. The 20 most important measurement values are also transmitted to the AGHS control system (by ABB) via ProfiNet and an OPC server for storage. Five digital signals (On, Ready, Start-up, Pumping, Alarm) are connected to the ABB system by hard-wire contacts.

Acknowledgments

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