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Parametric Study of a Divertor Cooling System for a Liquid-Metal Plasma-Facing Component

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***Abstract*— Novel divertor cooling system concept is currently under development at Princeton Plasma Physics Laboratory. This concept utilizes supercritical carbon dioxide as a coolant for the liquid lithium filled porous divertor front plate. Coolant is flowing in closed loop in the T-tube-type channel. Application of CO_2 eliminates safety concerns associated with water cooling of liquid lithium systems, and promises higher overall efficiency compared with systems using He as a coolant. Numerical analysis of divertor system initial configuration was performed using ANSYS software. Initially conjugated heat transfer problem was solved involving computational fluid dynamics (CFD) simulation of the coolant flow, and heat transfer in the coolant and solid regions of the cooling system. Redlich–Kwong real gas model was used for equation of state of supercritical CO_2 together with temperature- and pressure-dependent transport properties. Porous region filled with liquid lithium was modeled as a solid body with liquid lithium properties. Evaporation of liquid lithium from the front face was included via special temperature-dependent boundary condition. Results of CFD and heat transfer analysis were used as external conditions for structural analysis of the system components. Simulations were performed within ANSYS Workbench framework using ANSYS CFX for conjugated heat transfer and CFD analysis, and ANSYS Mechanical for structural analysis. Initial results were obtained using simplified 2-D model of the cooling system. The 2-D model allowed direct comparison with previous cooling concepts, which use He as a coolant. Optimization of the channel geometry in 2-D allowed increase in efficiency of the cooling system by reducing the total pressure drop in the coolant flow. Optimized geometrical parameters were used to create a 3-D model of the cooling system which eventually can be implemented and tested experimentally. The 3-D numerical simulation will be used to validate design variants of the divertor cooling system.**

***Index Terms*— Computational fluid dynamics (CFD), cooling system, divertor, lithium, numerical simulations.**

I. Introduction

PLASMA-FACING components (PFCs) have recently been highlighted as a critical area for research in the development of magnetic fusion energy (MFE) [1]. At present, tungsten PFCs are considered the lead candidate for future MFE experiments and devices. However, solid PFCs are subject to a range of failure mechanisms that will require machine-downtime and replacement of the PFC elements themselves. These failure mechanisms include transient-induced melting, flow and solidification of the metal PFC, often in a new, undesirable geometry [2]. A second failure mechanism occurs at steady-state and involves the gradual erosion and redistribution of PFC material throughout the vessel. Estimates of the erosive flux indicate that an ARIES-AT-type reactor might experience as much as 8000 kg of tungsten eroded and transported per operating year [3]. Such a large quantity of material represents a significant risk to the continued operation of a power reactor as well as its economic viability.

Liquid metal plasma-facing components (LMPFCs) are a potentially attractive technology for future power reactors. As a liquid metal can flow, in principle, a surface can be replenished *in situ* eliminating concerns of the overall lifetime of the PFC due to plasma impingement. Transient melting of the PFC surface is also eliminated as it is in a liquid state by design. Several liquid metals are typically considered for application as an LMPFC in a power reactor: Li, Sn, Ga, and alloys of the above [4]. Recently, the stability of a liquid metal in a porous substrate has been demonstrated in the NSTX device operating with liquid lithium [5]. This basic demonstration of the feasibility of a liquid metal PFC in a device of significant exhaust power and field strength motivates additional design studies to determine how an LMPFC concept may extrapolate to an MFE experiment.

Cooling technologies have been in development for solid PFCs for many years. While ITER will rely on water-cooled components, future power reactors are expected to operate with gaseous coolants in order to utilize a Brayton power-cycle. A high-temperature Brayton cycle provides higher thermal efficiency than might be achieved with a water-based Rankine steam cycle [6]. Cooling of the PFCs with a gaseous coolant, however, requires additional efforts as they are less effective than water-based systems [7]. Most concepts for high-heat flux components rely on impinging jets to increase the heat transfer coefficient locally and maintain material temperatures consistent with the structural materials used in the PFC design.

In this paper, we consider the usage of one example of a high-heat flux cooling system (the ARIES-CS T-Tube [8]) in the context of a liquid metal PFC (in this case, one based on lithium). A concept for a power-handling, liquid metal PFC has been proposed which utilizes porous or texturedsurfaces for surface stability while closely coupling the overall structure with the coolant which we refer to as an actively supplied, capillary restrained system [9]. Fig. 1 shows cartoon representation of the concept. The concept utilizes a close-coupling of the liquid metal surface with conventional cooling technologies to achieve a PFC that has the resilience provided

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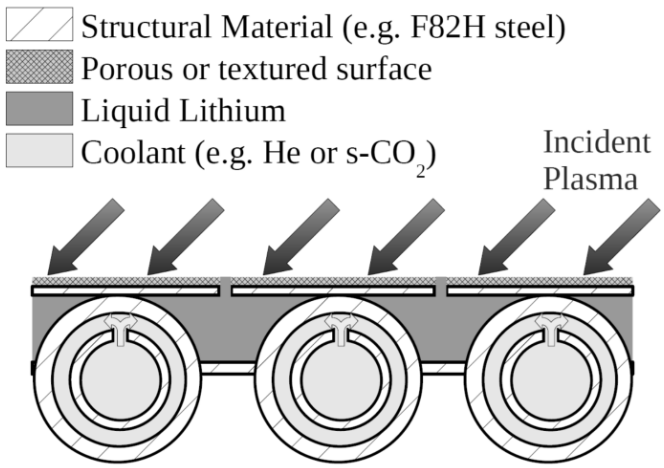

Fig. 1. Schematic diagram of the actively supplied, capillary restrained system. The basic concept features close-coupling of active coolant (here a T-tube scheme is shown), liquid metal reservoir (here liquid lithium), and a textured or porous front-face.

TABLE I

T-TUBE PARAMETERS FOR 2-D SIMULATIONS

Outer Tube OD	15mm
Outer Tube ID	13mm
Inner Tube OD	10.5mm
Outer Tube ID	8.5mm
Slot width	0.5mm

by the use of the liquid while also performing the necessary function of power extraction from the plasma. We will show 2-D and 3-D thermo-hydraulic calculations simulating this structure to determine the expected operating temperatures of such a liquid metal PFC and what implications arise from the surface temperatures. In addition to optimizations related to the geometry of the cooling scheme, we also consider the effect of alternative coolants. In this regard, we will show calculations comparing helium with supercritical-carbon dioxide (CO_2). This coolant is under active consideration for Generation-IV fission reactors due to smaller turbo-machinery and higher thermal efficiencies for identical turbine inlet temperatures versus conventional He cycles [10].

TABLE II

COOLANT PARAMETERS FOR T-TUBE SIMULATIONS

	Coolant	
	He	***Supercritical CO_2***
Inlet Temperature	185°C	185°C
Inlet Velocity	24.1 m/s	6.6 m/s
Outlet Pressure	10 MPa	20 MPa
Outer Tube OD	3.34	3.24

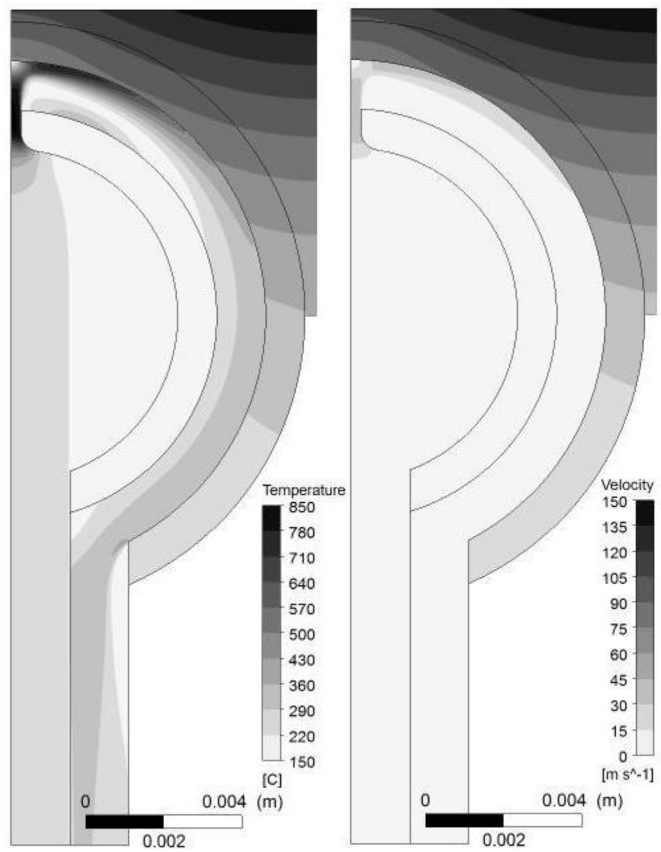

Fig. 2. Temperature distribution in the tungsten T-tube and velocity distributions in the gas. Constant heat flux of 10 MW is imposed on the armor. Parameters of the gas are adjusted to get the same maximum temperature on the armor. Left: He at 10-MPa and 24-m/s inlet velocity. Right supercritical CO_2 at 20-MPa and 6.6-m/s inlet velocity.

II. 2-D PARAMETRIC STUDIES

A. General Description

The 2-D parametric studies were performed using existing T-tube configuration [11] to study effectiveness of s-CO_2 as a coolant, and also to determine optimal tube diameter. Results were obtained using tungsten as a material for the T-tube and armor. With constant heat flux of 10 MW/m^2 imposed on the plasma facing surface.

Conjugated heat transfer analysis model was created using ANSYS CFX [12]. This model solves discretized Reynolds averaged Navier–Stokes equations to resolve flow of coolant. Simultaneously energy equation is solved to resolve heat transfer in both solid and fluid regions. On the interface between solid and fluid regions, nonslip conditions were imposed for the coolant flow using wall functions approach for turbulent flow. Conservation of the heat flux on fluid solid interface was also assumed. Temperature-dependent properties of the materials are used for solid parts. Real gas model with temperature- and pressure-dependent transport properties are used for s-CO_2. Ideal gas model with temperature-dependent transport properties is used for helium flow. Heat flux distribution on the font wall includes evaporative heat flux from the lithium surface. Detailed description of the numerical analysis procedure and validation of the model is presented in [11].

TABLE III
2-D T-TUBE SIMULATIONS RESULTS

	Coolant	
	He	***Supercritical CO_2***
Max Temperature	838°C	838°C
Volumetric Flow Rate	0.0361 $m^3/(s\ m)$	0.0099 $m^3/(s\ m)$
Total Pressure Drop	0.088 MPa	0.173 MPa
Pumping Power	3186 W/m	1716 W/m

B. Application of Supercritical CO_2

To evaluate performance of supercritical CO_2 as a cooling agent, we performed 2-D numerical simulations of the tungsten T-tube configuration. Parameters of the T-tube are presented in Table I. Constant heat flux of 10 MW/m^2 was imposed on the plasma facing wall of the armor. Performance was evaluated with He and CO_2 as coolants. Initial temperature of the coolant was the same in both cases: 185 °C. Other coolant parameters were chosen in a way that maximum temperature in the T-tube is the same 850 °C for both He and CO_2. Coolant parameters are presented in Table II.

Results of numerical simulations are shown in Fig. 2. Since the velocity of s-CO_2 needed to achieve the same cooling efficiency is much less than the velocity of He overall power required to pump the coolant is also smaller even though total pressure drop in the T-tube is higher when s-CO_2 is used. Results of the simulations are presented in Table III. Note that since this is a 2-D model results for the flow rate and pumping power are presented per meter length.

C. T-Tube Sizing

To evaluate effect of the tube sizing, numerical simulations were performed for the tungsten T-tube with dimensions presented in Table I as well as T-tube design with tube diameters scaled down with the factor 0.75, 0.50, and 0.25. For all cases, slot width and armor thickness remained the same. Constant heat flux of 10 MW/m^2 was imposed on the plasma facing wall of the armor. Initial temperature of the coolant was 60 °C for all cases. Velocity was adjusted so the mass flow rate per heated area was the same for all cases: 14 600 [(kg/s)/m^2].

Results of the simulations are shown in Figs. 3 and 4. Maximum temperature shown in Fig. 3 is reducing when pump is scaled down. This can be explained by reduction of the distance between front surface and coolant. Conduction through armor and outer tube has dominant effect on the heat transfer. So, reduction of the conductive path leads to temperature reduction.

Distributions on Fig. 4 show dramatic reduction in pumping power, pressure drop, and stress in the inner pipe, when the T-tube is scaled down. This can be explained by the fact that slot width is not reduced so the velocity in the slot is reduced when T-tube is scaled down and consequently hydraulic resistance in the slot is reduced. Reduction of the pressure drop due to the lower resistance in the slot leads to the reduction of the pumping power, and also to the reduction

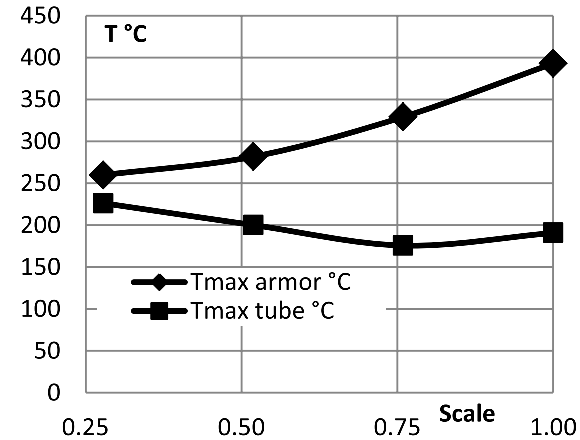

Fig. 3. Maximum temperature for the tungsten T-tubes of different scales.

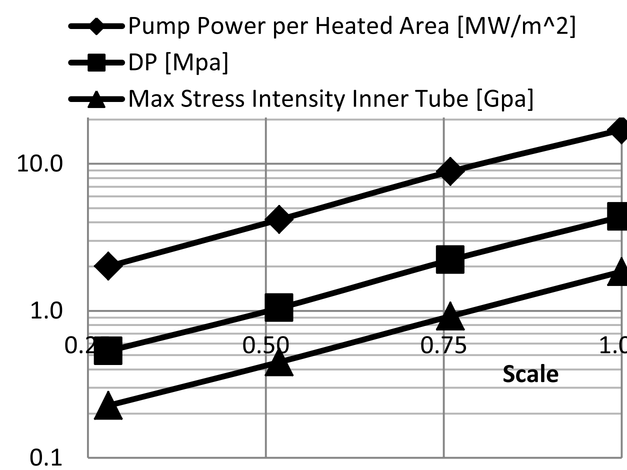

Fig. 4. Pump power, pressure drop, and cartridge stress intensity in the tungsten T-tubes of different scales.

of the stress on the inner tube, since major load on the inner cartridge is created by the pressure difference between inner and outer surfaces of the tube, which is determined by the pressure drop in the slot.

III. 3-D SIMULATIONS

A. Problem Setup

The 3-D numerical simulations were performed using F82H tubes and liquid lithium armor. Supercritical CO_2 with inlet temperature of 185 °C was used. The parts carrying liquid lithium are assumed solid with properties of liquid lithium approximated from the data in [13]

$$\rho_{Li} = 278.5 - 0.04657 \cdot T\,[K] + 274.6\left(1 - \frac{T\,[K]}{3500}\right)^{0.467} \frac{kg}{m^3}$$

$$c_{Li} = 4754 - 0.925 \cdot T[K] + 2.91 \cdot 10^{-4} \cdot T[K]^2 \frac{J}{kg \cdot K}$$

$$\lambda_{Li} = 22.28 + 0.05 \cdot T[K] - 1.243 \cdot 10^{-5} \cdot T[K]^2 \frac{W}{m \cdot K}.$$

Variable incidental heat flux was imposed on the front wall

$$q_{\text{ext}} = 2.1 + 10 \cdot e^{-|x[m]|/0.015} \frac{MW}{m^2}.$$

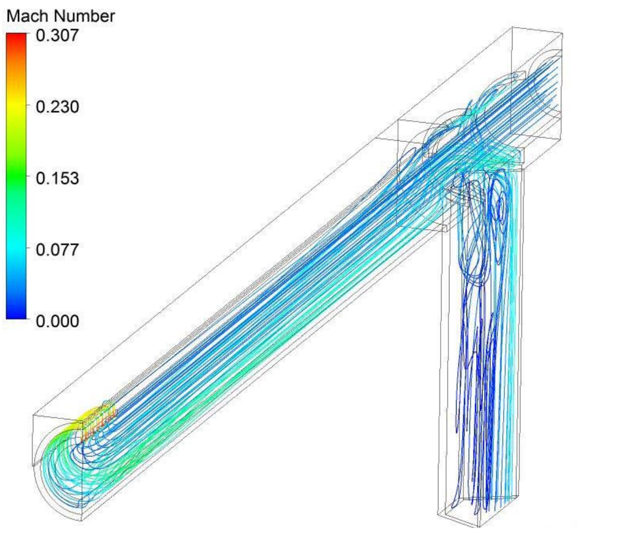

Fig. 5. 3-D numerical simulations of the T-tube cooling system. Stream lines colored by the values of the local Mach number.

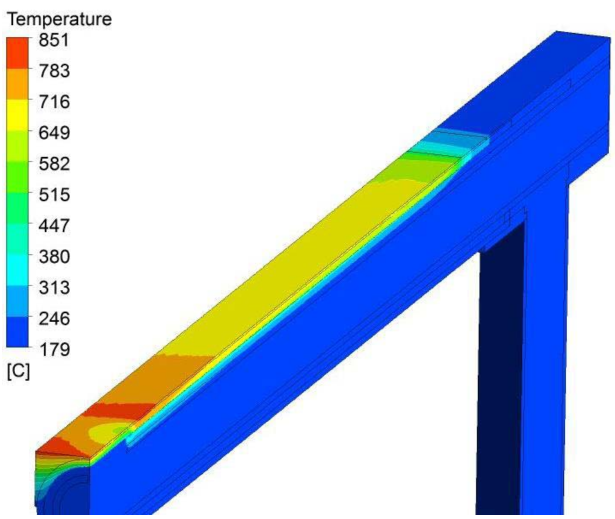

Fig. 6. 3-D numerical simulations of the T-tube cooling system. Temperature distribution.

This heat flux was corrected using lithium evaporative heat flux. Evaporation of the liquid lithium on the front surface was modeled as approximation of the data from [14]

$$q_{Li}^{\text{evap}} = \frac{145920\cdot 10^{9.3984+0.036322\cdot T[^\circ C]-2.1251\cdot 10^{-5}\cdot T[^\circ C]^2}}{6.02214\cdot 10^{23}}\frac{W}{m^2}.$$

B. Results of the Simulations

Results for the symmetrical T-tube simulations with s-CO_2 shown in Figs. 5–7 show that efficient cooling of the front surface can be achieved, with the flow rate of 0.3 kg/s, leading to pressure drop of 1.34 MPa, which results in the pumping power requirement of 1352 W. This gives power per unit length value of 4507 W/m when span of the heated region (0.3 m) is used as a length scale. This value is significantly higher than the value obtained using 2-D analysis and presented in Table III, which demonstrates importance of 3-D analysis for correct hydraulic loss prediction.

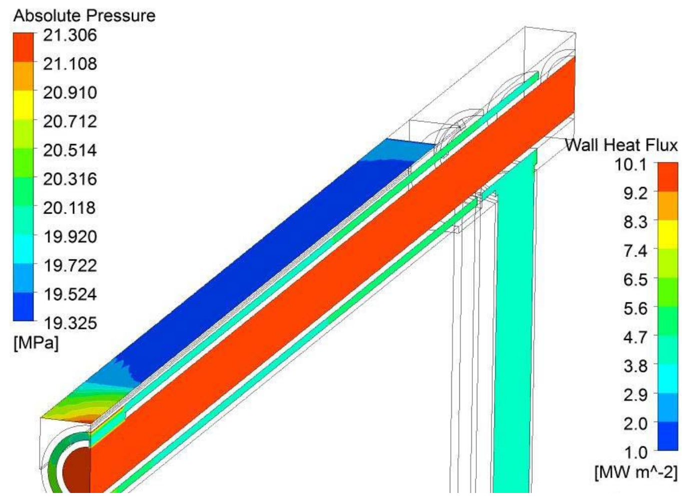

Fig. 7. 3-D numerical simulations of the T-tube cooling system. Coolant pressure distribution, and front wall heat flux distribution.

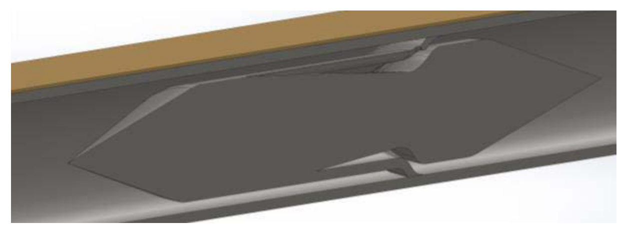

Fig. 8. Optimized T-tube-type insert design.

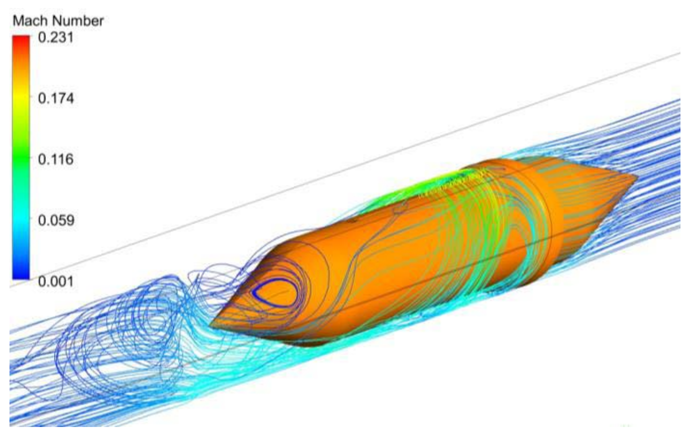

Fig. 9. 3-D numerical simulations of the T-tube cooling system. Stream lines colored by the values of the local Mach number.

Fig. 8 shows a cross section of the insert which allows creating an impinging jet situation similar to T-tube in the area of the maximum heat flux while maintaining main flow direction. Slot in the top of the insert creates a jet impinging on the channel wall at an angle, and in the general direction of the flow in the channel, which leads to reduction of overall hydraulic loss compared with normally impinging jet. Results for the optimized T-tube simulations shown in Figs. 9–11 show that efficient cooling of the front surface can be achieved, with the flow rate of 0.15 kg/s, leading to pressure drop of 0.59 MPa, which results in the pumping power requirement of 317 W.

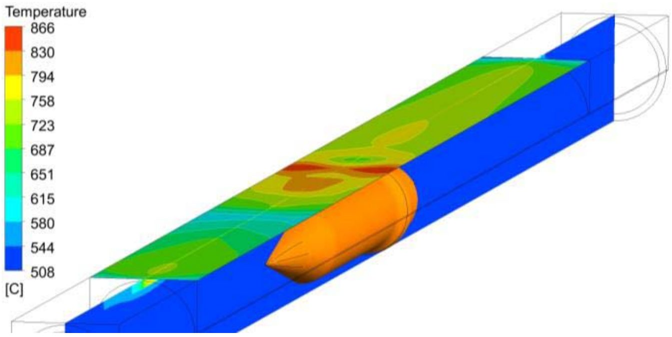

Fig. 10. 3-D numerical simulations of the T-tube cooling system. Temperature distribution.

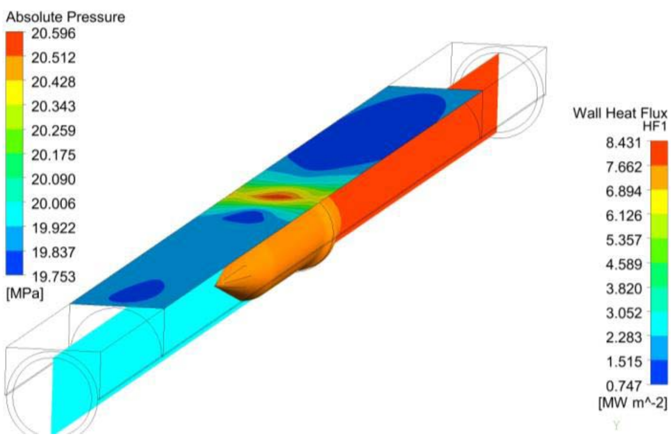

Fig. 11. 3-D numerical simulations of the T-tube cooling system. Coolant pressure distribution, and front wall heat flux distribution.

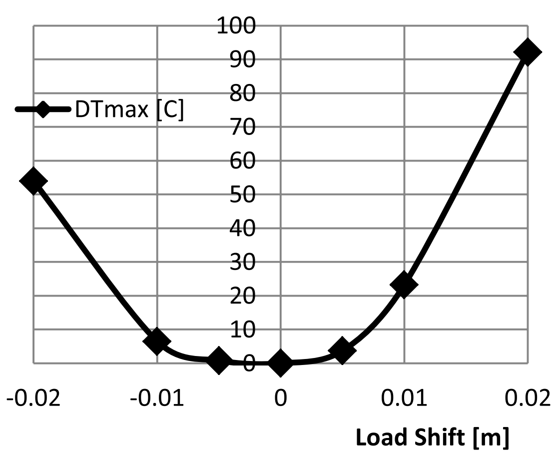

Fig. 12. Maximum temperature increase when the heat load is shifted.

C. Parametric Study of the Heat Load Shift

In this paper, maximum of the imposed heat flux on the front surface was shifted upstream or downstream of the coolant. Results in Fig. 12 show that maximum temperature increases <5 °C if load is shifted <5 mm in each direction. Increasing the length of the insert, with proportional increase of the slot, can extend the region to small temperature change beyond 5 mm. However, in this case, a higher flow rate may be needed to maintain sufficient cooling rate.

IV. Conclusion

Thermo-hydraulic simulations have been performed on a proposed LMPFC that would be suitable for use in a high-heat flux location. In this paper, we have considered further optimizations on the state-of-the-art schemes for gaseous cooling, namely the ARIES-CS T-tube [8]. Numerical studies of the geometry in 2-D and 3-D were carried out as well as consideration of the usage of s-CO_2 as an alternative coolant to He. It is shown that s-CO_2 can be used as an effective coolant in the divertor configuration and merits further study as a possible general coolant in a fusion power cycle. Further, the optimized T-tube configuration allows significant reduction of the pumping power at the comparative cooling rate. A study of the impact of shifting the peak heat-flux relative to the impinging jet of coolant shows that about 1 cm of shift can be tolerated without significant departure from the minimum temperatures—this allows for finite tolerances in a plasma-control system controlling the strike-point position in a real machine. These initially encouraging results motivate further studies on whether pumping power and overall cycle efficiency can be improved further.

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