Thermal Hydraulics Analysis of LIBRA-SP Target Chamber

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E.A. Mogahed

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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THERMAL HYDRAULICS ANALYSIS OF LIBRA-SP TARGET CHAMBER

E. A. Mogahed
Fusion Technology Institute, University of Wisconsin-Madison
1500 Engineering Drive
Madison, WI 53706-1687
(608) 263-6398

ABSTRACT

LIBRA-SP is a conceptual design study of an inertially confined 1000 MWe fusion power reactor utilizing self-pinched light ion beams. There are 24 ion beams which are arranged around the reactor cavity. The reaction chamber is an upright cylinder with an inverted conical roof resembling a mushroom, and a pool floor. The vertical sides of the cylinder are occupied by a blanket zone consisting of many perforated rigid HT-9 ferritic steel tubes called PERITs (PErforated RIgid Tube). The breeding/cooling material, liquid lead-lithium, flows through the PERITs, providing protection to the reflector/vacuum chamber so as to make it a lifetime component. The neutronics analysis and cavity hydrodynamics calculations are performed to account for the neutron heating and also to determine the effects of vaporization/condensation processes on the surface heat flux. The steady state nuclear heating distribution at the midplane is used for thermal hydraulics calculations. The maximum surface temperature of the HT-9 is chosen to not exceed 625°C to avoid drastic deterioration of the metal's mechanical properties. This choice restricts the thermal hydraulics performance of the reaction cavity. The inlet first surface coolant bulk temperature is 370°C, and the heat exchanger inlet coolant bulk temperature is 502°C.

I. INTRODUCTION

The scope of this work is limited to the thermal hydraulics analysis of the LIBRA-SP reaction chamber. Other issues of the design are discussed elsewhere.[1,2,3] The LIBRA-SP reaction chamber is an upright cylinder (Fig. 1). The vertical sides of the cylinder are occupied by a blanket zone consisting of many perforated rigid HT-9 ferritic steel tubes (PERITs) through which the breeding/cooling material, liquid lead-lithium, flows. In each perforation there is a special fan spray nozzle to maintain a very thin liquid vertical sheet which acts as a first protection surface. This way we assure having a continuously wetted metallic first surface due to splashing of the thin liquid metal sheet on the PERIT units with every target microexplosion. These fan spray sheets are overlapped to completely shadow the PERIT units. The radius to the first row of tubes is 4.0 m, the thickness of the blanket zone is 1.25 m and the length of the tubes is 10.6 m in two segments of 5.3 m each. There are two rows of 7 and 8 cm diameter PERIT units arranged at 14 cm between centerlines in the circumferential direction as well as between rows. These front tubes are configured to totally shadow the rear zone, and the spaces between the rows are determined from dynamic motion considerations. The rear tubes are 15 cm in diameter and there are 7 rows of them. Their sole function is to transport the PbLi which moderates neutrons and breeds T_2. There are vacuum tubes located behind the shield/blanket zone at the chamber midplane leading to an expansion tank situated below the reaction chamber. As the vapor flows into the expansion tank it exchanges heat with the PERIT units, and cools itself by virtue of an isentropic expansion. The chamber roof is not protected by PERIT units and for this reason is removed to a distance of 16 m from the target, also making it a lifetime component. Since the roof will be cooled, it also will condense vapor and have a wetted surface which will be vaporized after each shot. Another function of the mushroom shape is to protect the side walls which are shadowed by the PERIT units and to provide additional volume in the chamber for the vapor to expand into. The cooling units consist of two groups. The first is at the front (first surface units) and the second are solid curved circular tubes in the

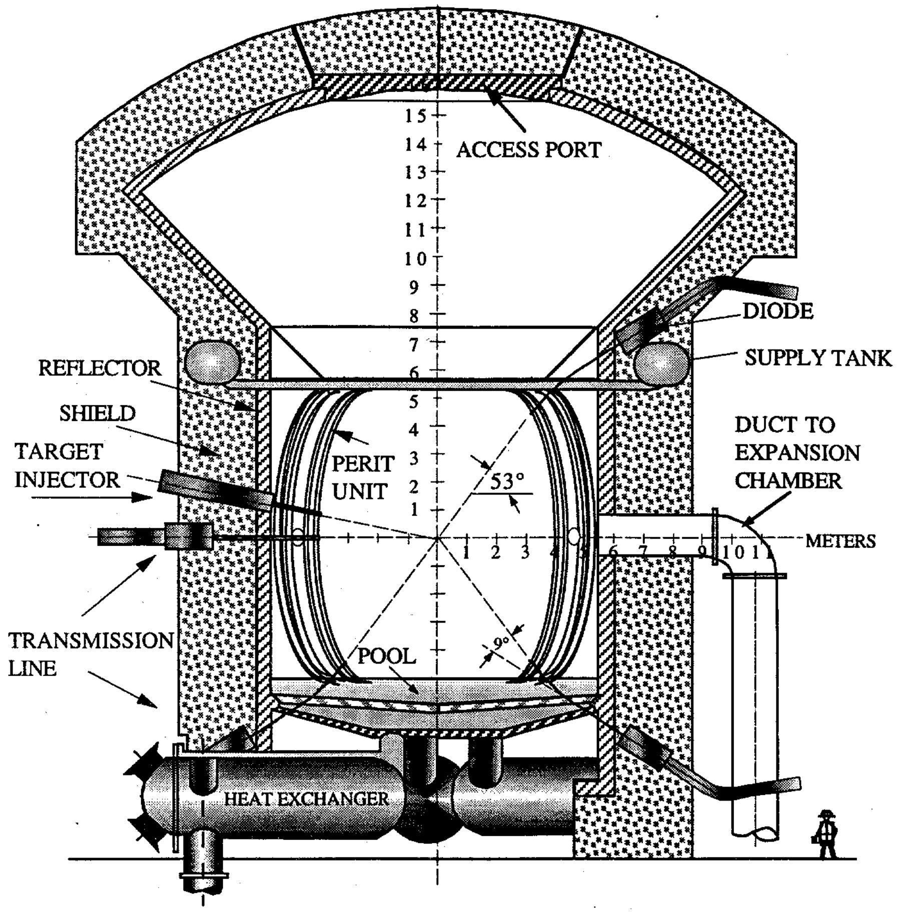

Fig. 1. A general cross-sectional view of the LIBRA-SP chamber.

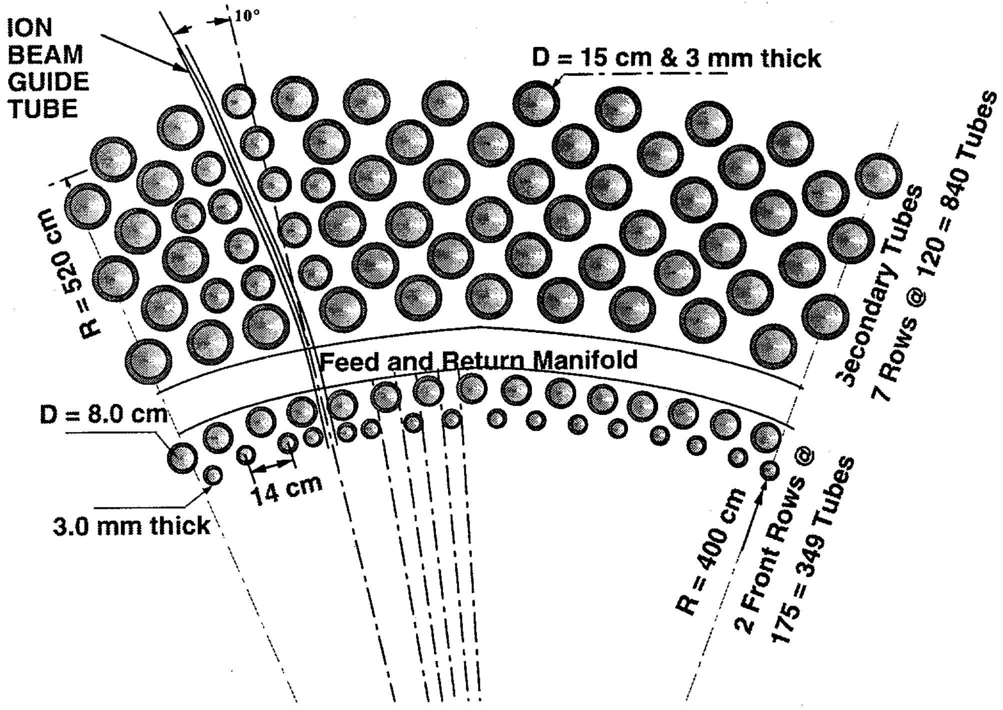

Fig. 2. A general layout of the PERIT units in the LIBRA-SP chamber.

TABLE I

General Parameters of the First Surface and Blanket

	The First Surface Unit		The Secondary Group
	PERIT	Second Row	
Number of rows	1	1	8
Number of tubes/row	175	175	175/first – 120/rest
Diameter of each tube (cm)	7.0	8	8.0/first – 15/rest
Diameter of the first row (cm)	800	-	440
Total number of tubes	175	175	1015

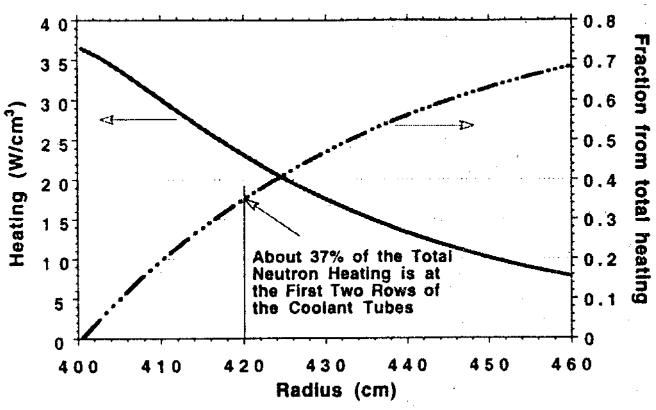

Fig. 3. Steady state nuclear heating distribution in LIBRA-SP and reflector.

back. Both are made of vertically curved austenitic stainless steel, low activation HT-9 tubing. Figure 2 shows the cooling unit placement. A detailed description of these two groups follows:

- First group: The front group consists of two rows of solid metallic tubing. Only the first row of tubes has perforated walls (PERITs). The second row group after the PERITs is staggered to close the gap between the PERIT tubes. The perforated walls of this system of tubing allow the internal coolant/breeder fluid to jet through the perforated walls (equipped with special flat sheet spray nozzles) and form flat thin vertical sheets of liquid metal as previously described.[1,2,3] Also, it wets the outer surface of the tube. The lead-lithium sheet jet and the wetted wall is designed to protect the metallic material from x-rays, charged particles and target/reaction debris.
- Second group: The secondary tubes consist of 8 concentric rows of solid HT-9 tubing. They are positioned in the back behind the feed and return manifold and act as a breeder blanket.

The general parameters for the first surface unit and the blanket geometry are in Table I.

II. THERMAL HYDRAULICS CALCULATIONS

Using the neutronics analysis results[4] along with the hydrodynamics calculations[1] the distribution of the volumetric nuclear heating in the blanket and PERIT unit and the effects of vaporization/condensation processes on the surface heat flux are readily obtained. The steady state nuclear heating distribution at the midplane is shown in Fig. 3. For thermal hydraulics calculations consider the following thermal load assumptions of the first surface (FS) of LIBRA-SP reactor:

- The first surface is the first two rows of coolant tubes (the first 20 cm of the blanket).
- According to the spatial distribution of the neutron heating, nearly 37% of the total neutron heating is generated in the first 20 cm of the blanket.
- All x-ray and debris power is consumed in heating, boiling, evaporating and superheating of PbLi (6.62 kg per shot).[1]
- All PbLi vapor will eventually recondense on the first surface only and cools down to 620°C. The maximum surface temperature of the HT-9 is chosen to not exceed 625°C to avoid drastic deterioration of the metal's mechanical properties. (This is a severe assumption and it is the worst case scenario. Actually, part of the PbLi vapor will condensate on other existing surfaces and some will be vented outside the cavity.)

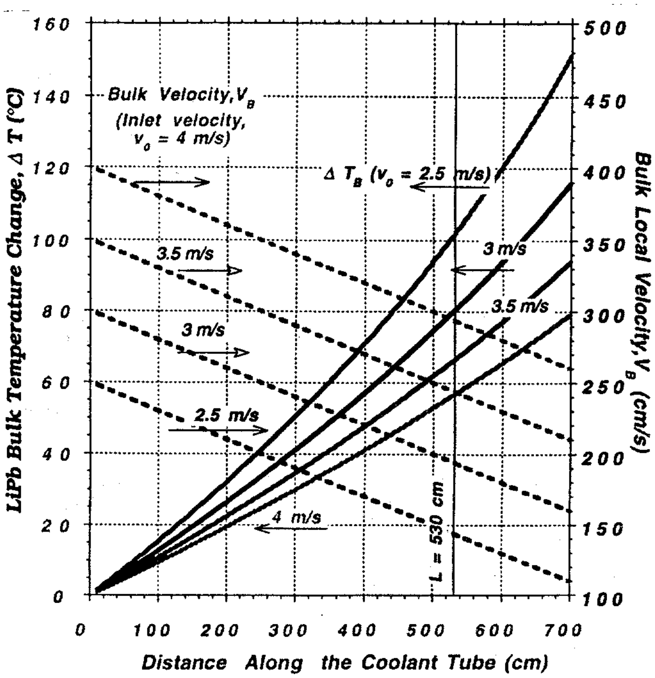

Fig. 4. The temperature variation and variation of coolant speed in the first row PERITs.

III. PROCEDURE

To fulfill the severe restriction on the maximum surface temperature of HT-9, a parametric study is performed to obtain the optimum design point. The length of the coolant tube is already determined according to the structural dynamics considerations[1,3] (5.3 m). The volumetric heating generated in the first two rows (first group) is about 37% of the total neutron heating in the cavity (Fig. 3) and the surface heating due to LiPb condensation is calculated. With this information in hand, the thermal hydraulic design calculations proceed to determine the required design parameters. It is important to note that due to the jet spray the average bulk coolant velocity is decreasing as the coolant advances along the coolant tube; the heat transfer coefficient changes from 1.8 W/cm^{2}K at a velocity of 3 m/s to 4 W/cm^{2}K at a velocity of 8 m/s for a coolant tube of 7 cm diameter. Figure 4 shows the variation of the bulk coolant velocity and the rise of the bulk coolant temperature as a function of distance along the coolant tube for various inlet coolant velocities. For a tube length of 5.3 m the design thermal hydraulics parameters are narrowed down to a few choices (Fig. 4).

The maximum difference between the inlet coolant bulk temperature and the maximum coolant tube surface temperature is obtained as a function of distance along the coolant tube for various inlet coolant velocities (Fig. 5). Keeping in mind the maximum surface temperature is 625°C and the minimum

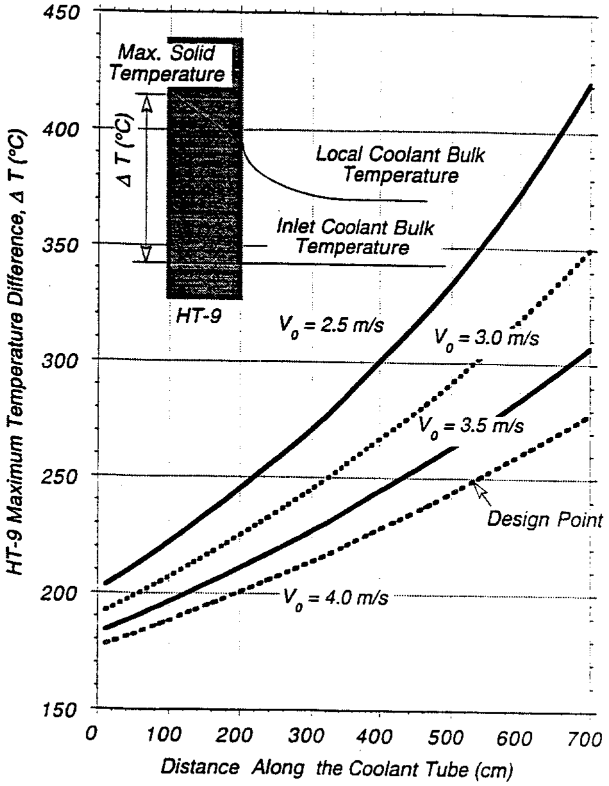

Fig. 5. Maximum temperature in the HT-9 of the first row PERITs.

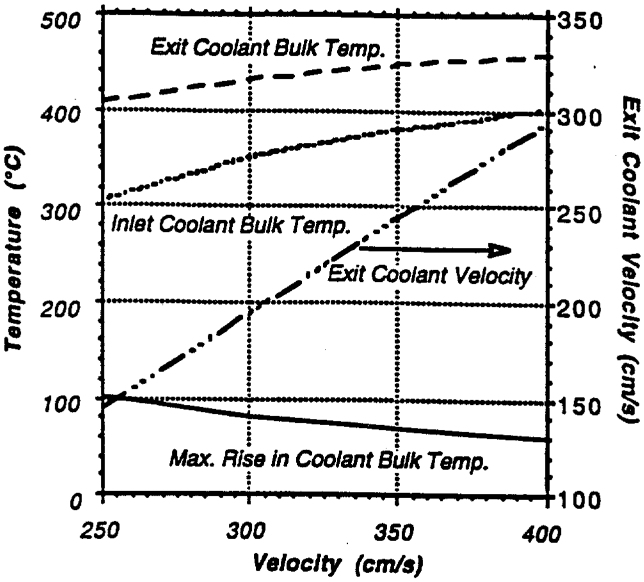

Fig. 6. Maximum coolant temperature of the first row PERITs.

TABLE II

Summary of Thermal Cavity Parameters

Number of coolant tubes in the FS	350
Total surface area (m^2)	1910.6
Weight of evaporated PbLi/shot (kg)	6.62
Repetition rate (1/s)	3.88
Thickness of PbLi recondensed per second (mm)	1.35
Heat flux due to recondensation at FS (W/cm^2)	107
Max. value of volumetric heating at FS (W/cm^3)	38.6
Average nuclear volumetric heating in front tube (W/cm^3)	35.03
Temp. rise in the coolant tube wall (HT-9 wall thick = 3 mm) due to:	
1. Surface heat flux only (condensation) (°C)	117.5
2. Volumetric heating only (°C)	7.5
Total temp. rise in the FS coolant tube wall (°C)	125
Max. FS coolant velocity (at inlet) (m/s)	4.0
Min. FS coolant velocity (at exit) (m/s)	2.9
Inlet FS coolant bulk temperature (°C)	370
Exit FS coolant bulk temperature (°C) (mass flow rate)	430 (32.32×10^4 kg/s)
Average coolant bulk temp. of outside coolant (°C)	650 (12.26×10^4 kg/s)
Exit blanket coolant bulk temp. (°C) (V = 17.4 cm/s)	600 (5.23×10^4 kg/s)
Total mass flow rate (kg/s)	49.78×10^4
HX inlet coolant bulk temperature (°C)	502
Pumping power (inside cavity) (MW)	47.61

inlet coolant temperature must be well above the freezing point of LiPb, the choice of the design point is now more focused. Figure 6 summarizes the change in the bulk coolant temperature fixing the maximum surface temperature at 625°C at the exit of a coolant tube of length of 5.3 m. Once the design point is determined the coolant temperature and the coolant mass flow rate at the exit of the coolant tubes from inside flow and outside flow (due to jet and condensation) are readily calculated. Table II summarizes the parameters at the calculated design point.

IV. TUBE SURFACE TEMPERATURE

A 2-D finite element model was prepared to analyze the thermal status of the PERITs at the midplane where the coolant exits from the upper section at 430°C. The same situation happens at the bottom where the coolant exits from the lower section at 430°C to the pool. For this analysis the following input values were used: coolant temperature, 430 °C; heat transfer coefficient, 2.2 W/cm^2K; HT-9 thermal conductivity, 0.268 W/cm^2K at 400 °C, and 0.278 W/cm^2K, at 650 °C; surface heat flux 107 W/cm^2; and tube thickness of 3 mm.

The maximum surface temperature reached is 619°C and the minimum temperature 489°C. The maximum temperature gradient across the tube wall thickness is 43°C/cm which is acceptable for thermal stresses.

ACKNOWLEDGEMENT

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