ENERGY CONVERSION IN FUSION REACTORS WITH LOOP HEAT PIPES

Flavio Dobran
New York, NY USA

Abstract:

The energy conversion technology of confined plasma fusion reactors is today in an early stage of development and requires significant improvements in simplicity, reliability, energy conversion efficiency, safety, and ability to handle steady-state and plasma disruption loads. Loop heat pipes are heat transport systems that could fulfill these requirements. Their operation is based on the evaporation and condensation of working fluids and the capillary pressures developed in the wicks of evaporators. This work presents a heat transfer performance analysis of a lithium cooled loop heat pipe module with different evaporator geometries suitable for cooling the blankets of fusion reactors. It is shown that such a module can remove large heat and neutron loads without requiring any external power to circulate the coolant through the module.

Key words: fusion reactors, energy conversion, heat pipes

1. Introduction The current world's power demand of 14 TW will increase significantly by the middle of this century [1]. Fossil fuels (coal, oil, gas) provide about 80% of this demand but by the end of this century these fuels will be significantly depleted and will have to be replaced with new high energy density sources. The energy released from the fusion of hydrogen isotopes deuterium and tritium is such a source and can provide most of the energy demand far into the future. Fusion has already been achieved in magnetically confined plasmas of several experimental reactors (TFTR, JET, JT-60), but this technology is not yet ready to be commercialized. The International Thermonuclear Experimental Reactor (ITER) is a magnetically confined plasma reactor that is currently being built by an international community and where 500 MW of fusion power is planned to be produced within a decade. It is anticipated that with this reactor some outstanding physics and engineering problems will be solved and that subsequently the first demonstration fusion reactor (DEMO) can be built before 2050 [2].

A key component of a commercial fusion reactor is the energy conversion system which has the function of transforming the energy stored in fusion reaction products (helium nuclei and neutrons) into other useful forms of energy. The energies of 3.5 MeV α-particles and 14.1 MeV neutrons produce heat and neutron fluxes in excess of 1 MW/m^2 on the first wall of the blanket and require advanced materials to absorb these loads. The neutrons cannot be confined by the magnetic field as the ions and electrons and are absorbed by the blanket where they deposit their kinetic energies, cause atomic displacements in blanket materials, and serve the purpose of producing tritium (fuel breeding) by interacting with an appropriate blanket coolant such as lithium or lithium compounds. Dobran [3, 4] evaluated the current energy conversion technology of magnetically confined plasma reactors and concluded that this technology has not yet been sufficiently developed for use beyond ITER where high plant efficiencies require that the blanket coolants and materials of the energy conversion system operate at high temperatures. Liquid metals have very high thermal capacities and can remove the anticipated fusion and neutron loads, but their use in high magnetic field environments of 5-10 T is not effective when flowing with large velocities, because of the prohibitive pumping powers required to overcome magnetohydrodynamic pressure drops. A promising technology that does not require any external power to circulate the coolant between the absorbing and rejecting heat exchangers employs heat pipes, but this technology has not been developed either [3].

The purpose of this paper is to report some results pertaining to the suitability of loop heat pipes [5] for removing first wall heat and neutron loads from fusion reactor blankets. The proposed design integrates a loop heat pipe into a module and employs an evaporating and condensing liquid metal that is also suitable for breeding tritium without requiring any external power to circulate the coolant through the module. Heat is removed by evaporating the liquid metal lithium in the evaporator with a wick and condensing the vapor in a condenser by transferring heat to a secondary coolant such as gas, liquid, or boiling fluid. The working fluid in the loop heat pipe circulates in the loop by the capillary pressure developed in the wick of the pipe. The heat absorbed by the secondary fluid can then be employed with the standard technology such as gas and steam turbines to produce electricity.

2. Loop heat pipe module

2.1. General considerations The inner chamber wall of ITER consists of 421 blanket modules, with a typical module being 0.5 wide and 1 m high [2]. These modules are water-cooled, each module can be removed for maintenance, and no tritium will be produced. Some experimental modules will, however, be cooled with helium and lithium-lead mixtures, and will employ lithium compounds for tritium production. This testing is necessary for designing tritium breeding liquid metal cooled blanket modules for possible use in DEMO. The design and testing of high operating temperature modules has, however, not yet been considered.

Figure 1 illustrates a typical loop heat pipe module working with lithium for potential use in high thermal efficiency fusion reactors. Here two different size wicks are employed for producing the necessary capillary pressure in the superheated liquid lithium flowing through the wicks. The closely spaced horizontal grooves in the evaporator serve the dual purpose of serving as fins for removing heat from the first wall and removing vapor from the evaporated liquid. This vapor is then collected in a vapor line and routed to a compact condenser where it is condensed on the outside of tubes carrying helium gas at high pressure and temperature. The condensed liquid flows through the liquid line into a compensation or accumulation chamber where it is heated to saturation and subsequently superheated as it flows through the secondary and primary wicks. It is this superheated liquid which then produces the required capillary pressure for pumping the working fluid through the loop. This design permits an effective separation of the evaporator and condenser, which is very important for interfacing the module with tritium removal and secondary coolant systems. In most places within the loop heat pipe module, the liquid lithium flows parallel to the strong toroidal magnetic field without producing a magnetic pressure drop that would otherwise contribute to a magnetohydrodynamic pumping power penalty. The heat of evaporation of lithium ($2x10^4$kJ/kg) is 10 times larger than that of water and thus a large heat transfer rate can be achieved with a small lithium flow rate. Small lithium flow rates are beneficial even when in some parts of the loop (wicks, liquid line) the liquid metal flows perpendicularly to the magnetic field direction.

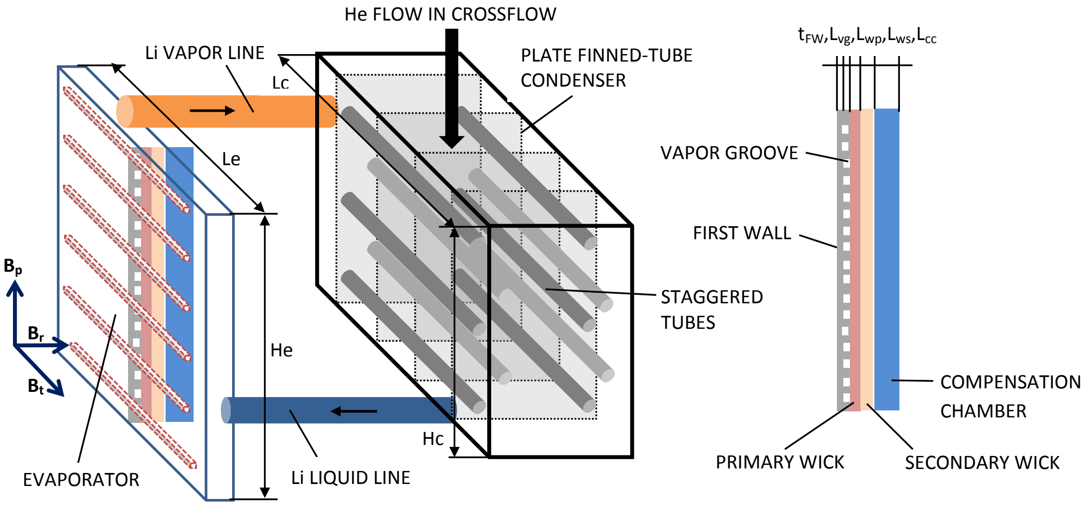

Figure 1: Schematic illustration of a loop heat pipe module for removing heat and neutron fluxes in fusion reactors. Patent pending.

2.2. Analysis While a fusion reactor has to operate in steady-state this cannot be guaranteed for all times, because of the possible milliseconds plasma disruptions which deposit very large heat fluxes of ions on the surfaces of blanket modules. These disruptions can produce large transients in the energy conversion system and a proper design of this system must account not only for overcoming the starting cooling loop transients, but also for these disruptions. In the preliminary evaluation of a loop heat pipe system for cooling the first wall of the reactor we will, however, ignore such transients and multidimensional effects and employ only steady-state, fully-developed, and one-dimensional mass, momentum, and energy balances to study the system. The flows can be laminar, turbulent, and transitional, and the flowing lithium can be exposed to the toroidal, poloidal, and radial magnetic fields (Fig. 1). The neutrons deposit their energies within the module and thus contribute towards the heating of the fluid that circulates through the loop, i.e.

$$q_n(x) = q_{nfw} e^{-\gamma x} \tag{1}$$

where x is the distance from the first wall and q_{nfw} is the first wall neutron fluence. γ=2.6 m^{-1} is the empirical constant determined by a neutronic analysis specifying the neutron distribution within the metallic module. The first wall heat flux q_{hfw} is also a parameter in the analysis and can be changed for parametric studies.

The steady-state fully-developed one-dimensional energy balances for the condenser employ the effectiveness-NTU approach for the superheated, saturated, and subcooled regions of the condenser, i.e

$$\epsilon \equiv \frac{Q_{c,sink}}{Q_{c,sink-max}} = \epsilon(NTU, \frac{C_{min}}{C_{max}}), \qquad NTU = \frac{UA}{C_{min}}, \qquad C = \dot{m}Cp \tag{2}$$

$$\frac{1}{UA} = \frac{1}{h_{ci}A_i} + \frac{R_{fi}}{A_i} + \frac{R_{fo}}{A_o} + \frac{1}{h_{co}A_o\eta_{cg}} \tag{3}$$

where $\dot{m}$ is the mass flow-rate of lithium. The thermal capacity and specific heat of lithium are C and C_p, and U, As, hs, Rs and η are the condenser overall heat transfer coefficient and areas, local heat transfer coefficients, thermal resistances of tubes, and fin efficiency, respectively. The pressure drop of coolant through parallel evaporator grooves, wicks, compensation chamber, vapor and liquid lines, and condenser accounts for frictional, momentum, and magnetic field losses. Generally,

$$\Delta P = \frac{\dot{m}^2}{2\rho_v N_{vg}^2 A_{vg}^2} + \frac{\dot{m} L \mu_\ell}{\rho_\ell A \phi K_w} + \frac{\dot{m} L \sigma_{e\ell} B_\perp^2}{\rho_\ell A \phi}\left(\frac{1}{H_{a\perp}} + \frac{C}{1 + C + \frac{a}{3b}}\right) + \sum_{i=1}^{m} S_i \frac{\rho_i V_i^2}{2}$$

$$H_{a\perp} = aB_\perp \sqrt{\frac{\sigma_{el}}{\mu_\ell}}, \quad C = \frac{\sigma_{e\ell} t_w}{a \sigma_\ell} \tag{4}$$

Here L and t_w are the evaporator length and wall thickness, $B_\perp$ is perpendicular-to-the-flow magnetic field, and $\sigma_{e\ell}$, μ_ℓ, ρ_ℓ, and V are the lithium electrical resistivity, viscosity, density, and mean velocity, respectively. N_{vg} and A_{vg} are the number of grooves and groove area of the evaporator, and ϕ and K_w are the porosity and permeability, respectively.

The total pressure drop of lithium through the loop cannot exceed the capillary pressure

$$\Delta P_{tot} \leq \Delta P_c = \frac{2\sigma}{r_{wp}} \tag{5}$$

and the wick temperature cannot exceed the boiling limit of the fluid, i.e.

$$T - T_{sat} \leq \frac{2\sigma T_{sat}}{h_{lg} r_{wp}}\left(\frac{1}{\rho_g} - \frac{1}{\rho_\ell}\right) \tag{6}$$

where r_{wp} is the wick pore radius, σ is the surface tension, h_{lg} is the enthalpy of evaporation, and ρ_g and ρ_ℓ are the vapor and liquid densities of lithium. T_{sat} is the saturation temperature of fluid.

The space limitation precludes a more complete presentation of the modeling equations for each component of the module (first wall, evaporator grooves, vapor line, condenser, liquid line, compensation chamber, and primary and secondary wicks). These equations can be solved numerically by specifying the geometry of the evaporator, condenser, and liquid and vapor lines, and their thermal and electrical properties; primary and secondary loop coolants (lithium and helium gas) and their thermodynamic properties; evaporator heat and neutron loads; and secondary loop coolant parameters (helium inlet temperature, pressure, velocity). The acceptable solutions of these equations must satisfy the above pressure drop and boiling temperature limitations and give the operating temperatures and pressures and mass flow-rate of the primary coolant in different components of the module.

3. Results Table 1 summarizes some preliminary results. Here L and H are the length and height of evaporator and condenser, t is wall thickness, V is mean flow velocity, Fp is the number of fins per unit length of condenser, D is hydraulic diameter, K_w is wick permeability, r_w is wick pore radius, a and b are half-widths of liquid line duct, N_{vg} is the number of grooves in the evaporator, H_{vg} and L_{vg} are the groove height and width, N_c and N_{cr} are the number of tubes in the two adjacent rows of the condenser, T_1 is the vapor temperature at the exit of evaporator, and T_8 is the mean fluid temperature in compensation chamber. The subscripts c, cc, e, fw, $\ell\ell$, p, s, vg, $v\ell$, w, wp, ws pertain to condenser, compensation chamber, evaporator, first wall, liquid line, primary, secondary, vapor groove, vapor line, wall, wick primary, and wick secondary, respectively.

The results show that by increasing the number of grooves in the evaporator produces lower module operating temperatures and lithium mass flow rates and higher loop pressure drops. Lower operating temperatures of modules place less demands on the developments of advanced materials (refractories and ceramics) while lower lithium mass flow rates lead to more compact designs and lower radioactive tritium inventories in modules. When using N_{vg}=1200, H_{vg}/L_{vg}=0.5/3 with T_g=900 K instead of T_g=700 K the upper operating temperatures of the module and lithium flow rate increase only slightly, but produces a significantly higher plant thermal efficiency.

Table 1: Parameters used in the analysis are: $B_{\perp e}$=5 T, $B_{\perp c}$= 5 T, $B_{\perp \ell\ell}$ =10 T, L_e=L_c= 0.5 m, H_e=H_c=1 m, t_{fw}=2 mm, L_{wp}=10 mm, L_{ws}=20 mm, L_{cc}=50 mm, T_g=700 K, P_g=8 MPa, V_g =3 m/s, Fp=710 1/m, t_f=0.15 mm, Dc_i=8 mm, Dc_o=10 mm, K_{wp}=10^{-13}m^2, K_{ws}=10^{-10}m^2, r_{wp}=10^{-5}m, r_{ws}=10^{-4}m, k_{fw}=100 W/mK, D_{vli}=100 mm, L_{vli}=1 m, a_{ll}=40 mm, b_{ll}=10 mm, L_{ll}=1 m, t_{we}=2 mm, t_{wvl}=2mm, t_{wll}=2 mm, Nc/Ncr=12/12, q_{hfw}=1 MW/m^2, and q_{nfw}=1 MW/m^3. The results in the table are for $\dot{m}$, T_1, T_8, and $\Delta P_{tot}/\Delta P_{cap}$, and correspond to different evaporator geometries N_{vg}, H_{vg}, and L_{vg}.

N_{vg}	H_{vg}/L_{vg} mm/mm	$\dot{m}$ g/s	T_1 K	T_8 K	$\Delta P/\Delta P_{cap}$ kPa/kPa
300	1.5/3	27.1	1862	1413	25.0/40.2
500	1/3	27.0	1854	1396	26.0/40.4
900	1/3	26.7	1806	1357	25.3/41.9
1200	0.5/3	26.5	1812	1325	33.1/41.7

4. Conclusions Loop heat pipes are promissing devices for removing large heat and neutron loads in fusion reactors. They can be integrated into compact modules for easy maintenance and breeding of tritium and do not require external power to circulate the coolant. A preliminary design of such a module is evaluated for the steady-state thermal performance with evaporating and condensing lithium as the primary and helium gas as the secondary working fluid and it is found that this configuration can remove the anticipated steady-state first wall heat and neutron fluxes. The evaporator and condenser of such a module allow for a very compact design and should require minimum maintenance. Small grooves in the evaporator produce low lithium mass flow rates and consequently cause very small magnetohydrodyanmic pressure drops in comparison to the momentum and frictional components. The investigated module designs operate below 1880 K and with micro grooves the operating temperatures can be reduced. This work suggests that loop heat pipes modules should receive further analytical and experimental evaluations that include operations under startup and transient heat flux and neutron loads as anticipated during the normal and plasma disruption conditions of fusion reactors.

REFERENCES

[1]. B. Dudley. *BP Statistical Review of World Energy* (BP, June 2015).

[2]. F. Romanelli. *Fusion Electricity: A Roadmap to the Realization of Fusion Energy* (EFDA, November 2012).

[3]. F. Dobran. Fusion energy conversion in magnetically confined plasma reactors. *Progress in Nuclear Energy*, vol. 60 (2012), pp. 89-116.

[4]. F. Dobran. Heat removal from the controlled thermonuclear reactor. *Magnetohydrodynamics*, vol. 48 (2012), pp. 177-189.

[5]. Yu.F. Maydanik. Loop heat pipes. *Applied Thermal Engineering*, vol. 25 (2005), pp. 635-657.