Heat Transfer in Fusion Starship Radiation Shielding Systems

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Abstract

Fusion starship designs may require radiation shielding from neutrons and X-rays created by the drive. Even nominally aneutronic fusion reactions, such as Deuterium+He3, can produce neutron fluxes through side reactions that will create large cooling requirements in drive structural elements.

Neutrons and X-ray emission levels are established for three fusion drive designs, Daedalus(1), a Daedalus variant and Icarus Firefly(2). From nearly zero for Daedalus, they rise to a few hundred GW for the Daedalus variant and to 8400 GW for Firefly. The geometric structure of the vehicles is analyzed in order to determine the impingement rate for the neutron and X-Ray radiation. The open nozzle proposed by Miernik(3) is used as an example of design. Firefly, the most severely heat loaded design, requires 260 GW of cooling, and the cooling system is the main mass of the ship, excluding fuel. Two methods are compared to remove the heat to the radiators, temperature change using $Q=m_f*cp*\Delta t$ for gas and liquid flows, and $Q=m_f*Ve$ for phase change. The fluid paths are determined and the Haaland approximation, $f= (-1.8*\log(((e/D)/3.7)1.11 + (6.9/Re)))^{-2}$ (4) is used to determine pump and compressor power requirements using the friction factor at fluid velocity. Then radiator areas and masses are determined. The radiators are sized using $Q=AeB(tr^4-ts^4)$ and iterative design based on the known thermal capabilities of materials. The physical arrangements of radiators are examined in regards to view factors, radiator placement and the influence of these on radiative power. Phase change in liquid metals provides the most powerful heat extraction method for the powers levels involved in starship propulsion, and that radiators need to be placed as close to the drive as possible to avoid important mass penalties. Use of gases as heat transfer fluids is particularily affected by the relatively poor conductive qualities of gases in pipes as determined by the Gnielinski correlation: $h= ((f/8) \times (Re - 1000) \times Pr) / (1+(12.7 \times (f/8)^{1/2} \times (Pr^{2/3} -1))) \times k/D$ (4).The following partial table lists materials for spaceship cooling using the vaporization phase change or the mass flow, for 100 GW of power.

Substance	Boiling point	Latent Heat of vaporisation (Ve)	Specific heat	Temperature difference required to equal vaporisation	for 500 C temp. diff. in fluid	By phase change
	K	kJ/kg	kJ/kg°C	°C	Tonnes/s	Tonnes/s
Helium	4	21	5.19	4	**39**	4762
Hydrogen	20	449	14	32	14	223
Water	373	2270	4.18	543	48	44
FLiBe*	1703	11433	2.4	4630	84	9
Lithium	1615	21159	3.58	5910	56	5
Beryllium	2742	32444	1.82	17827	110	3
Aluminium	2792	10500	0.897	11706	223	10

It is possible for starships with neutron and x-ray loads to have adequate performances despite mass penalties due to the cooling systems. Neutron and x-ray heating has important effects on vehicle mass and the reduction of neutron and x-ray emissions in the drive is a key part of fusion starship design.

Keywords: Fusion, heat transfer, heat transport, radiation

References

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