Reactor, Boiler & Auxiliaries - Course 133

BASIC HEAT TRANSPORT FLUID REQUIREMENTS

The basic objectives of the heat transport fluid are two-fold:

- to produce the highest temperature possible for maximum thermal efficiency and also
- to allow maximum energy to be extracted from the fuel without overrating (ie, to allow a high burn up).

Both of these objectives are achieved by optimisation of the properties, both nuclear and non-nuclear of the heat transport fluid some of which may be conflicting. These main properties are now discussed and compared for the possiblities which can be used for CANDU namely D_2O, H_2O and organic coolant.

NUCLEAR CONSIDERATIONS

(a) Neutron Absorbtion

For present CANDU reactors the most important criteria of good neutron economy dictates the use of D_2O which has the lowest neutron absorption cross section of any of the possible choices, and its use enables criticality using natural fuel to be achieved.

Typically the heat transport D_2O in core will absorb 0.5% of the neutrons which are absorbed parasitically in the core.

The alternative to D_2O in use in Canada is H_2O, in the BLW reactor Gl at Gentilly. Because of the increased neutron absorbtion of H_2O, fuel burn up is poorer than in CANDU and natural fuel can only maintain criticality on start up by initially inserting booster rods until $\approx$20% (by wt) quality is established in the channels. No more BLW reactors are however planned for Canada as a result of the success of the basic PHW CANDU design.

Other Canadian experience is with organic coolant such as used in the OCR 60 MW(th) experimental reactor at Whiteshell.

The coolant used, Monsanto OS-84 is a mixture of partially hydrogenated terphenyls and is a standard commercial product used in the plastics industry. Its absorbtion is between that of H_2O and D_2O, but this means that slightly enriched fuel must be used. Early fuel consisted of UO_2 enriched between 1.2 to 2.4 wt %. Present fuel is similarly enriched uranium monocarbide UC which allows higher element powers than UO_2 fuel.

(b) Moderating Ratio

A good moderating ratio is desirable but not essential for a heat transport fluid. If the heat transport fluid moderating ratio is high the amount of moderator may be reduced, the fuel channel separation can be smaller and hence reactor size and cost may be reduced. For the larger reactors now being designed this may not be an advantage as it is now becoming a problem to find space between channel end fittings just to bring out coolant feeder pipes from the central channels without congestion.

If the overall reactor void coefficient has a large positive (or negative) value then voids due to boiling of a heat transport fluid with a large moderating ratio would result in large power transients or flux tilts. An example of this behaviour is seen in the BLW reactor Gl which allows boiling in its vertical fuel channels.

(c) Induced Activity

The following criteria are desirable for the induced activity produced as a result of neutron absorption in the heat transport fluid:

- if γ activity is present it should be of low energy to reduce shielding requirements around equipment. Both D_2O and H_2O produce N-16 and O-19 which release high energy (6-7 MeV) γ's preventing on power access or maintenance with these coolants.

- the induced activity should be of short half life. Fortunately N-16 and O-19 have half lives of 7 secs and 27 secs which means equipment is accessible shortly after shutdown. The 12 year tritium half life in D_2O is a long term problem, the activity level building up to equilibrium over the station lifetime unless dilution with non active D_2O is done. As tritium emits no γ rays however the problem is one of leakage. Table 1 lists typical HT tritium activity levels for Pickering GSA.

Compared to H_2O and D_2O the organic OS-84 shows its great advantage because of the absence of N-16, O-19, tritium and activated corrosion products resulting in very low (2 mRem/hr) radiation fields surrounding the HT equipment during operation and shutdown.

(d) Radiation Stability

Radiolysis should be small for a heat transport fluid. D_2O and H_2O are relatively immune from this although hydrogen (and/or deuterium) gas is added to the HT system to maintain a low oxygen content as dissociated hydrogen (or deuterium) has a tendency to diffuse into pipework and pressure tubes which would otherwise have an excess oxygen concentration, increasing system corrosion. Due to the high pressure on the system however the radiolysis is not as rapid as in the low pressure moderator system.

Organic OS-84 is somewhat worse for irradiation stability changing its chemical and physical properties which modify its coolant characteristics, increasing its vapour pressure. Gases, volatiles and high boilers produced by radiolysis (and also pyrolysis) have to be removed by degassing and making up with fresh or reprocessed coolant.

TABLE I

CHEMICAL ANALYSES FOR PICKERING GS

(September 26, 1973)

Heat Transport System	Unit 1	Unit 2	Unit 3	Unit 4
pH	10.5	10.5	10.7	10.7
conductivity mS/m	2.7	2.5	2.7	2.8
lithium mg/kg	1.7	1.4	1.4	1.2
chlorides mg/kg	< 0.1	< 0.1	< 0.1	< 0.1
iodine - 131 μCi/kg	2.2	34.1	60.5	16.2
D_2O weight %	97.80	98.20	98.00	98.30
Dissolved D_2 cc/kg	17.2	22.1	15.4	21.3
Dissolved O_2 μg/kg	< 4	< 4	< 4	< 4
tritium Ci/kg	0.334	0.325	0.334	0.150

NON NUCLEAR CONSIDERATIONS

(a) Heat Transport and Pumping Power

As a heat transport fluid, water (H_2O or D_2O) is attractive having higher specific heat and thermal conductivity compared to alternative coolants such as nitrogen, carbon dioxide gas or organics such as OS-84. As a result of this the pumping power required (for the same heat removal) for water is much less than for a gas coolant.

The pumping power needed to transport the coolant through the system depends upon the following factors:

pumping power = pressure drop x volume flow rate

The limiting factor on the pumping power to be supplied depends upon the extent of the pressure drop (loss) in the primary circuit. At Bruce, for example, the loss is about 1.5 MPa which is $\approx$15% of the operating pressure. Most of this loss is friction loss in the system and does however reappear as heat in the system.

The limiting factor on the flow rate, and heat on the heat removal rate, is dictated by coolant velocity in the channels, high velocities causing chafing and wear of the pressure tubes by the fuel. CANDU channel coolant velocities are usually limited to less than 10 m/sec.

As well as increasing the flow rate through the channels to increase the heat transfer we can further subdivide the fuel into more elements and the new 37 element Bruce bundle (producing 800kW) is a step in this direction. The limit to further subdivision is the temperature gradient in the fuel and the sheath temperature and, also the additional absorbtion of the increased volume of zirconium.

To improve the heat transport properties of pressurized D_2O the use of partially boiling D_2O or H_2O is attractive and offers some advantages. Boiling the coolant allows better heat transfer from the fuel and can provide a higher steam pressure for the same coolant outlet temperature and pressure. In addition better fuel burn up is obtained (especially with H_2O) by increasing the coolant steam quality.

With boiling H_2O (Gl) the low density available with $\approx$20% boiling allows natural UO_2 fuel to be used and also allows the use of a direct steam cycle eliminating the need of main boilers. The limit to boiling allowed in the channels is dryout of the fuel sheath. This is the condition at which the boiling condition provides only steam blanketing of the sheath resulting in a large temperature rise (and hence fuel melting) to transfer the power.

As well as the disadvantage of boiling cooling being closer to dryout limits than a pressurized coolant, the flow characteristics of the 2 phase steam/water results in zone control problems due to the localized density fluctuations which can occur.

(b) Boiling Point and Freezing Point

Ideally the coolant temperature should be as high as possible for maximum thermal efficiency and so a high boiling point, low vapour pressure liquid is desirable so the heat transport system can be at the lowest possible pressure.

The high boiling point, low vapour pressure of organics gives them an advantage over water systems so that little pressure (only 2.2 MPa, inlet, for OS-84 coolant) is needed for a (higher) temperature of 400°C. In addition, thinner (3.2 mm) zircaloy may be used for the pressure tubes. A disadvantage of this is that the boiler steam side pressure is greater than the coolant pressure so that boiler tube leaks are into the coolant.

As far as freezing points are concerned D_2O has a minor problem (FP = 3.8°C) in that any cooling on heat exchanger service water supplied at less than this temperature may result in freezing but this is of more concern with moderator system D_2O.

With organic OS-84 the presence of high boilers increases the viscosity at low temperatures and also results in the risk of freezing while shutdown and cooled. Continuous coolant make up reduces this problem.

(c) Corrosion Properties

Corrosion of the heat transport system materials must be minimized because of possible deterioration, flow restrictions and contamination with active isotopes such as Co^{60} and Cu^{64}.

With water coolant and low cobalt content carbon steel heat transport piping, stainless steel end fittings and zircalloy tubes a pD $\approx$ 10-11 is maintained in the system by LiOD or ND_3 addition to minimize corrosion. (The stainless steel moderator system, by contrast, is kept at a pD of 7.4 as a result of the boron poison requirements of this system.)

The corrosion problem increases with oxygen content of the heat transport fluid and with D_2O or H_2O. This is minimized by the addition of D_2 (and/or H_2) gas to the system.

With organic OS-84 coolant corrosion rates are very low and are controlled by degassing the coolant, using nitrogen cover gas blankets and a dechlorinator system.

(d) Flammability and Thermal Stability

Water coolants are stable as far as these properties are concerned but organic coolant systems must be provided with automatic fire extinguishing equipment due to the possibility of ignition in air. In addition to decomposition by radiolysis the organics also undergo pyrolysis which, as previously mentioned is controlled by routine bleeding and make up of the coolant.

(e) Cost

The current cost of D_2O on the world market is $\approx$130$/kg making both the capital cost (Bruce/unit $\approx$570 Mg D_2O) and make up and upgrading costs higher than any alternate coolant. Even with the larger make up and reprocessing qualities of organics, D_2O still remains the most expensive coolant.

ASSIGNMENT

1. What are the advantages and disadvantages of using H_2O and D_2O as the heat transport fluid, compared to gases, organics or liquid metals? Organics, with negligible radiation fields, low pressure operation and low cost look like a good alternative to D_2O coolant. Why do we not use them at present?

2. The Bruce reactors have some boiling ($\approx$3% quality) in the outer channels. Why is this?

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