LA-UR-22-20580

Approved for public release; distribution is unlimited.

Title: Niowave Ancillary Systems – FY21 In Partial Fulfillment of the Deliverable Requirement for Niowave Ancillary Systems Support by LANL

Author(s): Singh, Bhavini
Woloshun, Keith Albert

Intended for: Report

Issued: 2022-01-24

Niowave Ancillary Systems – FY21

In Partial Fulfillment of the Deliverable Requirement for Niowave Ancillary Systems Support by LANL

Bhavini Singh, Keith Woloshun

1 Introduction

Niowave Inc. produces medical radioisotopes within the US. Lead-bismuth eutectic (LBE) is irradiated using an electron beam to produce neutrons that are used in the production of Molybdenum-99 (Mo-99). The medical community relies on a steady supply of Mo-99 which is primarily used in medical diagnostic imaging. The irradiation of LBE results in high temperatures within the molten metal, this work focusses on the design of ancillary systems associated with the liquid metal system.

The LBE is initially at a temperature of 200^0C and flows over a steel plate to create a waterfall. The electron beam is then aimed at the waterfall to generate neutrons. The peak temperatures of the LBE post irradiation depend on the beam energy of the LINAC. For a 15 MeV and 20 kW beam, the temperatures can range between 300^0C and 350^0C. The LBE is cycled through the system to create a closed loop that requires the post-irradiation LBE to be cooled back to 200^0C. This work focuses on the heat exchanger and condenser system responsible for the cooling of the post-irradiation LBE.

2 Previous LBE system design and performance

Niowave Inc. ran a thermal-hydraulic test with heater cartridges operating at 7.2 kW and 20.5 kW with one of the goals being to investigate the operation of a parallel flow heat exchanger used to cool the LBE.

The co-flow heat exchanger had a length of 12 inches, inner pipe ID 0.87 inches, OD 1 inch and outer pipe OD 2 inches. The water, which came in subcooled, at about 20^0C was passed through the outer pipe while the LBE flowed through the inner pipe. The steam generated from the cooling process was then released out of the building via a copper pipe.

Table 1 shows a small subset of the data from both the tests. The analysis that follows focused on one case from 20.5 kW tests, highlighted in the table.

Table 1: Selected test parameters showing heat exchanger performance

Test Conditions		Manually Recorded Data	Digitally Recorded Data		Calculated Data
Operating power (kW)	LBE Temperature (°C)	Q2 (water flow rate) (GPH)	T8 (Heat exchanger inlet temperature) (°C)	T9 (Heat exchanger outlet temperature) (°C)	LBE Flowrate (GPM)
7.5	350	1.6	350.8	338.2	4.3
		1.2	348.6	340.7	7.0
		2.0	349.6	345.3	10.0
20.5	350	7	374.8	346.3	7.6
			376.7	349.0	7.6
			38.2	359.0	9.5

The heat that was deposited in the LBE was calculated using Equation 1.

$$q = \dot{m}_h c_{p,h} \Delta T_h \tag{1}$$

Where the subscript h is for the hot fluid (LBE), c_p is the specific heat capacity of LBE at the temperature in the table and ΔT is the temperature difference of the LBE at inlet and outlet, T8 and T9 in the table respectively. The mass flow rate $\dot{m}$ was calculated using the volumetric flow rate in the table and the density of LBE at 350^{0}C. From these calculations, for the case highlighted in Table 1 it was found that approximately 20.4 kW of heat was dissipated in the LBE.

2.1 Pool boiling regimes within the heat exchanger

Given that the flow rate of the water in the heat exchanger was fairly slow, 7 GPH, on the order of 1e-6 m^3/s, we can approximate pool boiling heat transfer, where the fluid flow is due primarily to the buoyancy driven motion of bubbles. If we further assume that the subcooled water heats up rapidly, the water in the outer pipe of the heat exchanger is saturated and a typical pool boiling curve can be used to approximate the regime of pool boiling in which this heat transfer problem lies.

Assuming that the LBE completely fills the inner pipe of the heat exchanger and that the axial conduction along the pipes is negligible and further that the heat exchanger is insulated from the surroundings, the heat flux in the water can be calculated as:

$$q'' = \frac{q}{\pi L (D_o - D_i)} \tag{2}$$

where L is the length of the heat exchanger and in contact with water and D_o and D_i are the outer and inner pipe diameters respectively. The heat flux was 8.4e5 W/m^2 and the temperature difference between the heat exchanger surface (approximated as LBE temperature) and the saturation temperature of water (100 ^{0}C) was 274 ^{0}C for. Using a typical pool boiling curve to determine the boiling regime, these results indicate that the heat exchange occurred in the film boiling regime. In this regime, the surface temperature of the pipes of the heat exchanger are very high, and can result in failure of the equipment.

3 Proposed new design of LBE system

The new cooling system operated at Niowave will circulate LBE at 2 GPM. The initial temperature of LBE, before irradiation will be 200 ^{0}C and after irradiation, the heat exchanger will need to dissipate approximately 20 kW of heat. The heat exchanger proposed to cool the LBE is the same as those used in the previous analysis shown in Section 2, with inner diameter 0.87 inches, outer diameter 1 inch and length 12 inches. The LBE that needs to be cooled flows in the inner tube and water flows in the outer tube.

3.1 Proposed design

Niowave has not designed and tested the existing heat exchanger under the proposed new design. Based on our theoretical calculations, applying 20 kW of heat to 200 ^{0}C LBE will raise the temperature by about 100 ^{0}C (Equation 1), taking density of LBE at 200 ^{0}C to be approximately 10806 kg/m^3 and c_p at 200 ^{0}C to be approximately 146 Jkg^{-1}K^{-1} according to [1].

To calculate the temperature at the tube LBE surface, $T_{s,2}$ shown in the figure below, Equations 3 and 4 are used, where a simplified analysis is performed using thermal resistances, under the assumption of steady state, one-dimensional conduction.

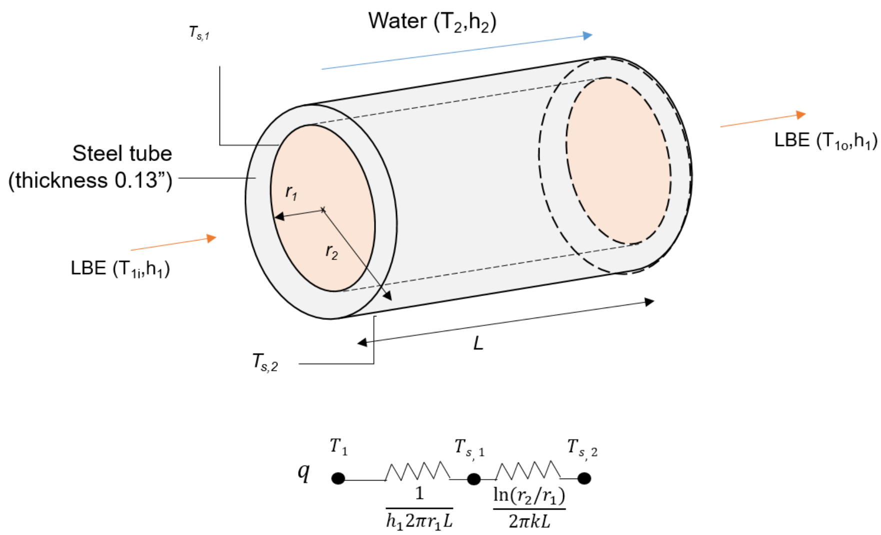


Figure 1: Schematic of LBE and water flow through the heat exchanger

$$q = UA\left(T_1 - T_{s,2}\right) \tag{3}$$

Where U is the overall heat transfer coefficient, and UA is related the total thermal resistance as shown in the equation below.

$$UA = \frac{1}{R_{tot}} = \frac{1}{\left[\frac{1}{h_1 2\pi r_1 L} + \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi k L}\right]} \tag{4}$$

Where $h_1 = \frac{Nuk_f}{d_1}$ where Nu is the water Nusselt number and k_f is the thermal conductivity of LBE and k in Equation 4 is the thermal conductivity of steel.

From the simplified analysis $T_{s,2}$ is estimated to be 34 ^{0}C with an inlet LBE temperatures of 300 ^{0}C, pipe length of 12 inches and inner diameter 0.87 inches. Therefore, the water in the heat exchanger will not boil and therefore the 20 kW of heat in the LBE cannot be dissipated.

The ideal boiling regime that we would like the heat exchanger to perform at is the nucleate boiling regime, which would require surface temperatures ($T_{s,2}$) greater than 105 ^{0}C and less than 130 ^{0}C. Note that these are approximate values, not accounting for any impurities present in the water, and based on the assumption of pool boiling in the heat exchanger, as in the analysis presented in Section 2.

To achieve these surface temperatures, we recommend that the heat exchanger length be increased to 17 inches, or the inner pipe diameter increased to 1 inch, with the length maintained at 12 inches.

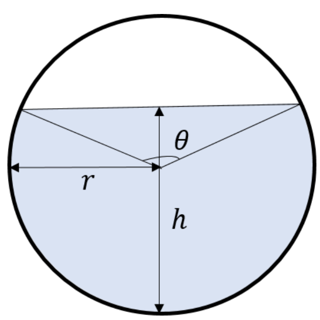
3.2 Potential issues with LBE build up in the heat exchanger

The current LBE system design uses a pump to flow the LBE into the converter, creating a waterfall. This LBE once irradiated then flows out to the heat exchanger which is placed at an angle of approximately 3 ^{0}. The outward flow of LBE is driven purely by gravity.

We use the Gaukler-Manning formula used mainly in open channel flow or flow in partially full conduits to estimate whether the current design will allow for the LBE to flow without build up. The use of this empirical equation (Equation 5) assumes a value for the Gaukler-Manning coefficient, a value that is not well estimated for molten metal flows.

$$\dot{V} = \frac{1}{n} R_h^{\frac{2}{3}} A S^{\frac{1}{2}} \tag{5}$$

We use here a coefficient value (n) proposed by Steilan [2] of 0.052 (compared to 0.012 for water) under the understanding that the surface roughness of the steel pipe, velocity of LBE and temperature of LBE play a large role in determining this coefficient. The hydraulic radius (R_h) is calculated as A/P the ratio of the cross sectional area of the flow, A to the perimeter , P. A schematic of the perimeter and area of the flow for a pipe that is more than half full are shown in the figure below.



$$A = \pi r^2 - \frac{r^2(\theta - \sin\theta)}{2}$$

$$P = 2\pi r - r\theta$$

$$R_h = A/P$$

Figure 2: Schematic of flow area and perimeter for a partially full pipe

In the current heat exchanger design, with a tilt angle of 3^0 and inner pipe diameter of 0.87 inches, based on the estimates from the Gaukler-Manning formula, the maximum achievable flow rate for gravity driven flow, would be approximately 0.84 GPM. This would mean that there is buildup of LBE which was initially pumped at 2 GPM. Based on these calculations, we propose either an increase in the tilt angle to 15 ^{0} or an increase in the inner pipe diameter to 1.2 inches.

Experiments are needed to determine with confidence, whether the current design and the proposed designs, allow the LBE to completely fill the inner tube, without build up.

3.3 Condenser design

The current LBE system vents the steam generated in the heat exchanger out of the building though copper pipes. This system will be changed to a closed loop system where a condenser will be installed to convert the steam generated in the heat exchanger to water, that will be circulated back into the heat exchanger to cool the LBE. Niowave has proposed a helical tube heat exchanger with initial sizing an analysis.

4 Future work

LANL has undertaken the task of building an LBE test loop to test heat exchanger and condenser designs suited to an applied heat load of 20 kW. This set-up will also investigate the flow of LBE in the heat exchanger and propose designs that mitigate LBE build up.

References

[1] Sobolev, V. (2011). Database of thermophysical properties of liquid metal coolants for GEN-IV.

[2] Stelian, C. Application of Manning's Formula for Estimation of Liquid Metal Levels in Electromagnetic Flow Measurements. *Metall Mater Trans B* **46,** 449–458 (2015). https://doi.org/10.1007/s11663-014-0206-9