

# Numerical Investigation of Molten Lead Flow in a Closed Loop to Estimate Pressure Demand

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## INTRODUCTION

A facility is being established at the University of New Mexico to study flow accelerated corrosion due to molten lead to support Lead-cooled fast reactor development. A particular goal of the project is to assess the compatibility of various structural materials with molten lead at high temperatures  $> 550\text{ }^{\circ}\text{C}$  and velocities  $> 3\text{ m/sec}$ . The facility consists of an electromagnetic (EM) pump driven loop which is heated by 21 kW radiant heaters and cooled by natural circulation of air. As both the lead flow rate and the pressure drop are unknown prior to experiments, numerical simulations are utilized to estimate the flow rate and pressure demand which are constrained by the supply and demand curves. Since the desired velocity in the sample holder channel is  $> 3\text{ m/sec}$ , numerical simulations are used to decide whether or not multiple sample holders could be used. Additionally, simulations are conducted to study the multiphase interactions and distribution of lead and argon in the expansion tank. The work described herein assumes uniform temperature distribution in the loop and ignores natural convection. Estimates of velocity and pressure obtained herein will be used in future work to inform a natural convection model and iteratively correct the estimates of the flow rate and the pressure demand.

## EXPERIMENTAL FACILITY

Figure 1 shows a schematic drawing of the lead loop and its main components. The loop consists of an EM pump, an expansion tank, a heat exchanger, primary and secondary melt tanks, and sample holder(s). The secondary melt tank is used to control the purity of lead before it's transferred to the primary melt tank. An electromagnetic pump is used to circulate the molten lead in the loop with a target velocity of 3 m/sec in the sample holder channel in order to study flow accelerated corrosion which results from coupled erosion-corrosion [1, 2]. Prior work on lead and lead bismuth corrosion in the literature used velocities up to 2 m/sec [1, 2]. However, it's desired to study greater flow velocities in order to understand the behavior of structural materials in molten lead environments at a wider range of conditions. The lead flow rate is monitored through the use of a heat exchanger relying on the amount of heat transferred.

Radiant heaters (21 kW) are used to achieve desired operation temperatures and to prevent the molten lead from freezing. Argon and hydrogen gases are used to control the oxygen levels in the loop. Oxygen levels are monitored using instrumentation in the expansion tank.

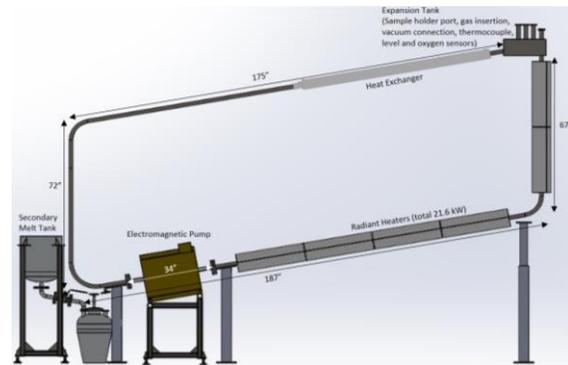


Fig. 1. Schematic drawing of the lead loop.

## METHODS

Numerical modeling of the entire loop is not computationally practical because of the size of the mesh required. Simple circular pipes occupy the vast majority of the loop. Modeling the entire piping is, therefore, not the optimal approach. A more efficient approach is to model a section of the pipe and other components of the loop in separate simulations. Pressure drop can then be characterized as function of pipe length allowing extrapolation to the entire pipe length in the loop. The components selected for numerical modeling are shown in Figure 2. These components are (a) a 1.2 m long section of the pipe, (b) a sample holder (with eight samples inserted – not shown), (c) an expansion tank which contains both argon gas and molten lead.

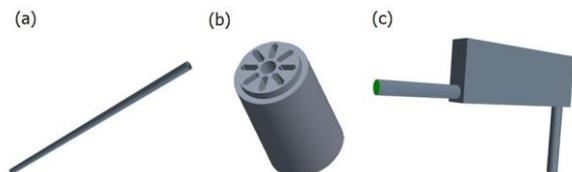


Fig. 2. Select components for numerical modeling.

The present work aims to calculate a first order estimate of the flow rate in the loop and the total pressure demand; neither of which are known. To achieve that purpose, computational fluid dynamics (CFD) simulations are utilized to estimate the pressure demand as function of the flow rate. The intersection of the pressure demand curve with the EM pump's pressure supply curve is the equilibrium state that the system would eventually reach. The effective flow rate in the system and the pressure demand could then be determined from that intersection. Commercial CFD package, STAR-CCM+, is used to simulate the flow across a section of the main pipe, the sample holder, and the expansion tank at different inlet flow rates. STAR-CCM's built-in surface remesher and polyhedral remesher were used for meshing the geometries. The generated meshes were relatively coarse ( $Y^+ > 10$ ) although they contained 14 million cells in expansion tank case and  $> 110$  million cells in the sample holder case (with 1.3 meter extension pipe). To compensate for the high  $Y^+$ , a high  $Y^+$  wall model was used in the simulations. A section of the computational mesh is shown in Figure 3. The figure also illustrates the placement of the samples in the sample holder. As a side note, the 1.3 meter extension pipe was added at the inlet of the sample holder so that the flow develops before it reaches the sample holder as it's of interest to characterize the velocity distribution in the sample holder channels.

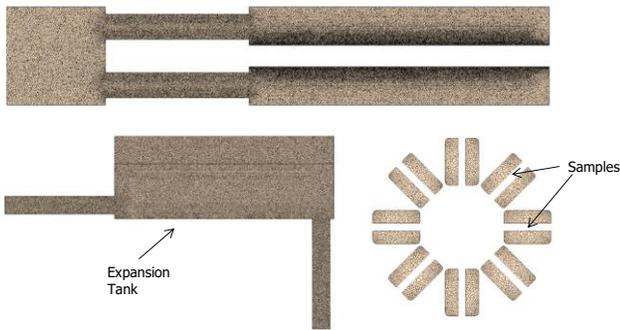


Fig. 3. A Portion of the computational mesh.

The present simulations assume a uniform temperature of  $550\text{ }^\circ\text{C}$  in all components. The properties of molten lead are evaluated at  $550\text{ }^\circ\text{C}$  [3]. In the real case, the temperature distribution in the system is not expected to be uniform. However, calculation of the temperature distribution in the system requires knowledge of the flow rate as lead flow transports heat from one part of the system to another. Therefore, the process is inherently iterative since the estimate of the flow rate itself depends on the temperature distribution. The simulations conducted herein are implicit, unsteady simulations for segregated, incompressible flow. A K-Omega turbulence model is employed as a closure to the Reynolds-averaged Navier-Stokes equations (RANS).

Second-order convection gamma transition is used with an intermittency minimum of  $1.0\text{E-}10$ .

## RESULTS

Lead flow was simulated at four different inlet flow rates ( $0.000138, 0.000277, 0.000553, 0.00083\text{ m}^3/\text{sec}$ ) for all three components considered as shown in Figure 4. The greatest pressure drop in all components was in the sample holder. This is due to the narrow channels of the sample holder and the drag at the inlet of the sample holder as the fluid transitioned from the main pipes to the sample holder. The pressure drops across different components were not equally sensitive to changes in flow rate. For instance, the pressure drop in the sample holder and the main pipes increased by factors of 2.25 and 2.13, respectively when the flow rate was increased from  $0.000553\text{ m}^3/\text{sec}$  to  $0.00083\text{ m}^3/\text{sec}$ , while the pressure drop across the expansion tank only increased by a factor of 1.28.

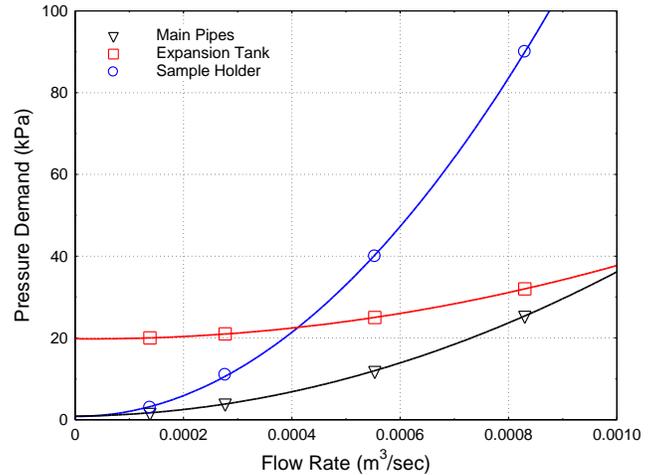


Fig. 4. Pressure demand as function of flow rate.

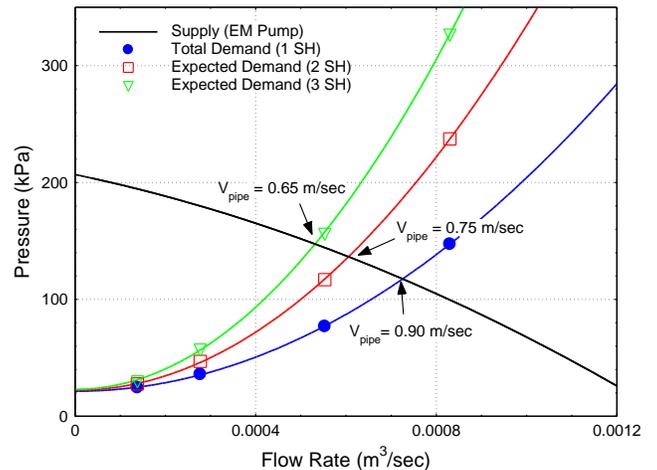


Fig. 5. Pressure supply vs. demand curves.

The pressure drops across different components were summed up in order to obtain the total pressure demand curve as function of flow rate as shown in Figure 5. Three scenarios were considered. In the first scenario, only one sample holder with eight samples was considered in the system. In the second and third scenarios, multiple sample holders were considered with eight samples each. For the 2 and 3 sample holder cases, the pressure drop due to the sample holder was arithmetically added up. This operation wouldn't be applicable if the sample holders were joined together as the inlet conditions would be different. Figure 5 shows that the effective pressure demand would be ~117 kPa for the one sample holder case leading to a flow rate of 0.00072 m<sup>3</sup>/sec. This flow rate corresponds to an average velocity of 0.90 m/sec in the main pipes. When second and third sample holders are added, the average velocity in the main pipes drops to 0.75 m/sec and 0.65 m/sec, respectively. This drop in flow velocity is expected as a result of the increase in pressure demand which shifts the equilibrium state as shown in Figure 5.

As it's desired to achieve a flow velocity of 3 or more m/sec in the sample holder channels, it's necessary to investigate the flow in the sample holder. Figure 6 shows the velocity and turbulent kinetic energy distributions in the sample holder channels. An inlet velocity boundary condition of 0.90 m/sec was used based on the estimate of the equilibrium state in the entire loop for a case of one sample holder. For that case, it was found that the average flow velocity in the channel was ~3.4 m/sec. The flow velocity is not uniformly distributed along the sample holder channel. It's observed that the velocity is highest at the entrance of the channel when the flow transitions from the main pipe to the sample holder. After that the flow gradually becomes more evenly distributed along the sample holder. As a result, the samples are more likely to be eroded near the entrance of the sample holder channel than at the end of the channel since the shear stresses would be greater.

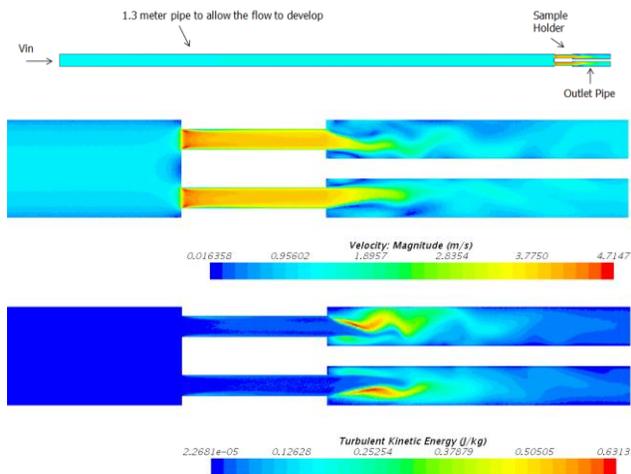


Fig. 6. Velocity and TKE distribution in the sample holder.

The distribution of the turbulent kinetic energy shown in Figure 6 indicates that turbulence is relatively concentrated in the outlet pipe beyond the sample holder. The turbulent kinetic energy in the sample holder channel is stronger than that in the main pipes leading to the sample holder. This turbulence may facilitate the erosion of the sample leading to increased flow accelerated corrosion effects. The average velocity in the sample holder channel can be correlated to the flow rate in the main pipe. A linear relationship is observed as shown in Figure 7. The average flow velocity in the sample holder channel drops below 3 m/sec when multiple sample holders are used. In the case of 2 and 3 sample holders, the average flow velocity in the sample holder drops to 2.8 m/sec and 2.4 m/sec, respectively. Given that the desired velocity in the sample holder channel is 3 m/sec, it's safe to conclude that using 3 sample holders would not be feasible unless the design of the sample holder is modified to reduce the pressure drop. Since the estimated velocity in the 2 sample holder case is 93% of the desired velocity, it's necessary to conduct additional investigations of the flow to eliminate some of the assumptions made in the present calculations such as the uniform temperature distribution assumption before arriving at conclusions.

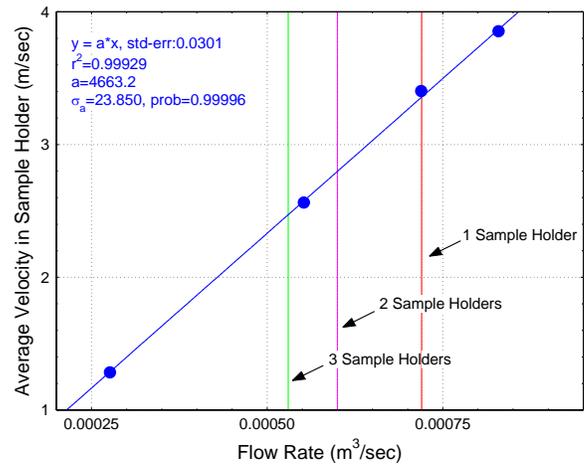


Fig. 7. Velocity in sample holder vs. flow rate.

Finally, the flow in the expansion tank was investigated. The simulations used the volume of fluid (VOF) method with 2<sup>nd</sup>-order convection. An Eulerian multiphase mixing scheme was employed with volume-weighted dynamic viscosity. Adaptive time-stepping was used to satisfy the Courant-Friedrichs-Lewy (CFL) numerical stability condition. The initial state was defined such that argon occupied the top 60% of the expansion tank by volume at 20 kPa. It should be noted that the initial level of lead was above that of the outlet pipe. Further, it was assumed that the flow at the inlet of the system was 100% lead. This assumption would not be accurate if argon could exit the expansion tank and enter the main pipes.

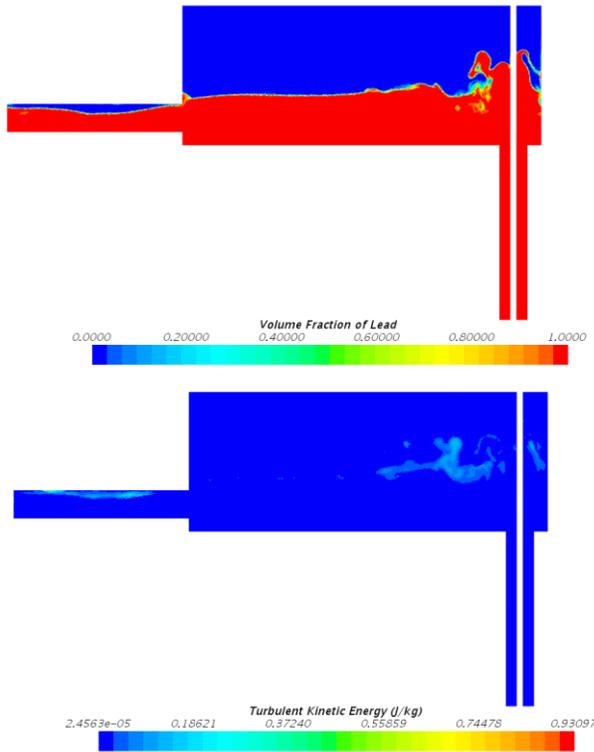


Fig. 8. Volume fraction of lead and TKE distribution in the expansion tank.

Figure 8 shows the distribution of the volume fraction of lead in the expansion tank. It is observed that the level of lead is higher close to the inlet pipe and lower towards the outlet pipe. As a result, some argon is present in the outlet pipe. Since the timescale of the simulation is in the order of a few seconds, it's not possible to conclude that argon would be present in the main pipes in the long-run. However, turbulent mixing of argon and lead near the inlet should be noted. It is due to the increased turbulence at the lead-argon interface. Lead from the inlet pipe is flowing upwards towards argon. As lead is denser than argon, it ends up going downwards in the opposite direction of the flow at the inlet resulting in turbulent mixing in that region. This is reflected in the turbulent kinetic energy distribution which shows stronger turbulence at the lead-argon interface near the inlet pipe.

## CONCLUSION

Numerical simulations were conducted to aid with decision-making in the development of an experimental facility to study flow accelerated corrosion due to molten lead flow. One of the experimental design challenges is developing an efficient sample holder design that would allow multiple samples to be tested in parallel and at the same time allow the flow velocity to be above 3 m/sec in its channels. Numerical modeling of the entire loop at once is

not computationally practical as the length of the loop is more than 12 meters and the Reynolds number is  $> 10^5$ . The approach used in this work was to model the major components and a section of the pipe. The total pressure drop is then obtained by adding the pressure drop in all components in addition to that of the pipe extrapolated to its entire length. The pressure drop was obtained as a function of flow rate using numerical simulations. The intersection of the pressure demand curve with the pump supply curve represents the equilibrium state at which the system would operate. It was found that the flow velocity in the sample holder channel would be 3.4 m/sec if one sample holder was used. If two or three sample holders were used, the velocity would drop to 2.8 and 2.4 m/sec, respectively. Based on that, it's apparent that the design of the sample holder would need to be modified to allow for more than 2 sample holders to be used. However, it should be noted that the present simulations assumed uniform temperature distribution throughout the system and considered disjointed sample holders. Since the properties of lead are temperature dependent, the pressure drop and flow rates would be affected by the uniform temperature assumption. Future work will use the flow rate estimate from the present work and simulate natural convection to investigate the temperature distribution in the loop and to correct the flow rate estimate.

## ACKNOWLEDGEMENTS

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