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Experimental Operation of a Prototype 750C Advanced Chloride Molten Salt Bellows Valve

Kenneth Armijo[1,*], Aaron Overacker[1], Ansel Blumenthal[1], Jeffrey Parish[2], Michael Nelson[2], Ivica Radman[2], and Javier Martell[1]

[1] Sandia National Laboratories, USA

[2] Flowserve Corporation, USA

*Correspondence: Kenneth Armijo, kmarmij@sandia.gov

Abstract. To achieve DOE 2030 SunShot targets that reduce the cost of liquid-based solar by an additional 40% to 70% beyond 2018 costs, a more reliable, highly manufacturable flow valve, capable of achieving operational temperatures of >700°C is required [1]. This paper investigates the development of an innovative high-temperature chloride molten salt valve, with operation up to 750°C. This valve is intended to be employed within Gen 3 CSP liquid-based thermal energy storage (TES) systems as well as Gen 4 modular salt reactor (MSR) technologies. This work details the general design and flow testing of a bellows-seal flow control valve (FCV). This design includes an integrated closed-loop thermal control system to ensure robust design for freeze-thaw cycles. The self-contained thermal management STM system, is unique in the salt valve industry since it is an integrated solution to provide a consistent, repeatable alternative to typical heat tracing. Additionally, the design includes the employment of a novel heat pipe valve stem to facilitate enhanced passive thermal management into the valve assembly. This valve stem heat pipe is designed to facilitate natural circulation within the bonnet to ensure robust operation, during both nominal and transient thermal operation. The valve body and trim will be designed using SS316H, consistent with Flowserve Corporation's existing product base and is code qualified but will utilize clad material for materials corrosion, manufacturing cost reduction and compatibility to ensure design flexibility. A test campaign was performed in this investigation utilizing a novel 750°C ternary chloride (20%NaCl/40%MgCl2/40%KCl by mol. wt. %) molten salt flow loop. A discussion about the design and installation of the valves within this test bed is provided for this investigation. Valve test results from this study assessed *Cv* curves as well as multiple actuator cycles, under varying thermodynamic and operational mode conditions, which would be characteristic within a commercial molten salt facility. The results indicate nominal operation for the baseline design, though improved performance and reliability is expected with the full designed FCV.

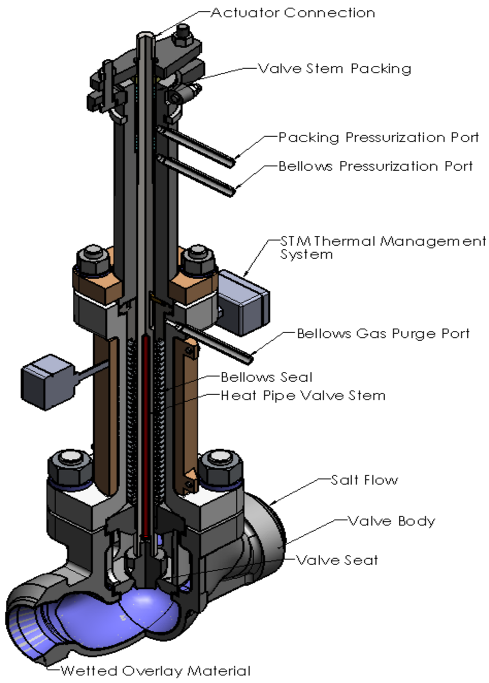
Keywords: Molten Salt, Experimental Valves, Heat Pipes

1. Advanced Valve Design

1.1 Bellows FCV Design

Bellows FCV's are utilized within high-temperature molten salt systems to reduce risks associated with salt leakage during varying operational thermodynamic and actuation conditions. The prototype globe FCV was developed with respect to high-temperature materials for the pressure containing valve components and highly responsive pneumatic/hydraulic actuation systems. During high-temperature molten salt operation, valve packing is exposed to extremely harsh conditions requiring regular maintenance on a 3–6-month basis. The design incorporated multiple purge ports to allow inert gas buffer layers between the bulk liquid and the packing materials. This improves the reliability of the pressurized sub-assembly materials, particularly with respect to thermal cycling. Another major valve reliability issue is internal salt freezing which can cause thermal-mechanical stress on valve stems. The novel heat pipe design addresses this freezing issue by using the hot working fluid as a heat source. This component passively transmits heat internally through the valve stem to the packing area, maintaining a constant internal temperature through the bellows and extended bonnet areas [2]. Employing a valve stem heat pipe keeps the valve hot if hot salt is present while allowing for enhanced freeze-recovery and reduced O&M.

A bellows valve design, Figure 1, was developed in this investigation which included the key components necessary for the valve design. The layout includes the initial stem sealing (packing) and bellows design, the STM (Self-Contained Thermal Management) system, and the valve stem heat pipe.



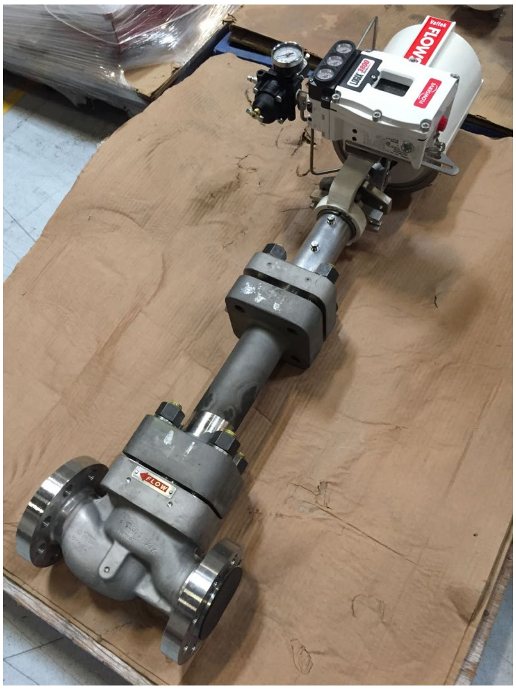


Figure 1. *Advanced Bellows FCV Design.*

The bellows stem sealing design included a back-up set of valve stem packing, a bellows gas purge port, a bellows pressurization port, and a packing pressurization port. The bellows gas purge port allows accumulated gas to be purged from the top of the bellows. The bellows pressurization port allows the inside of the bellows to be pressurized so the differential pressure across the bellows is reduced, thus significantly increasing the cycle life of the bellows. The packing pressurization port pressurizes the packing so that if the packing leaks, the pressurization gas leaks into the valve instead of the molten salt leaking out of the valve.

The initial preliminary valve layout included this stem sealing system. The team down-selected materials where the maximum allowable stress values for these materials of construction are shown in Table 1.

Table 1. *Material properties of bellows valve structural components.*

Component	**Material**	**Min Tensile Strength (ksi) Room Temp**	**Min Yield Strength (ksi) Room Temp**	**Allowable Stress (ksi) Room Temp**	**Allowable Stress (ksi) 1382°F**
Body [3],[4]	N06230 Casting	110	45	30	7.35
Bellows [3],[4] Housing	N06230 Casting	110	45	30	7.35
Bonnet [5]	A479-347H	75	30	20	2.752 7.9 @ 1200°F
Bonnet Flange [5],[6]	B564-N06230	110	45	30	7.35 15.6 @ 1200°F
Housing Guide [5]	B572-N06230	110	45	30	7.35
Bellows Fitting, Upper [5]	B572-N06230	110	45	30	7.35
Plug Stem	B572-N06230	110	45	30	7.35
Plug Head	B572-N06230	110	45	30	7.35

1.2 STM Design

Figure 2 presents an integrated and self-contained thermal management (STM) package, that is designed to provide a consistent and repeatable alternative to typical heat tracing. The STM is an active thermal management system is intended to provide a consistent repeatable alternative to heat tracing. It is installed around the bellows housing to provide a uniform, highly controllable heat load to the valve. The STM is critical for accurate thermal monitoring and control of the bonnet and packing areas in molten salt valves. This design incorporates a DiamondBack® trim, which has a unique ability to buffer pressure surges and pulses in a passive manner as salt passes through the trim; resulting in superior operability and performance of the valve. The design is resistant to choking, allowing much higher CV flow capacities for a given trim and valve size. The lack of 90-degree features ensures trim is robust and erosion resistant. This design is developed from the basis of the current Flowserve Valtek Mark One valve platform which is proven to be robust in highly corrosive and high-temperature applications [7].

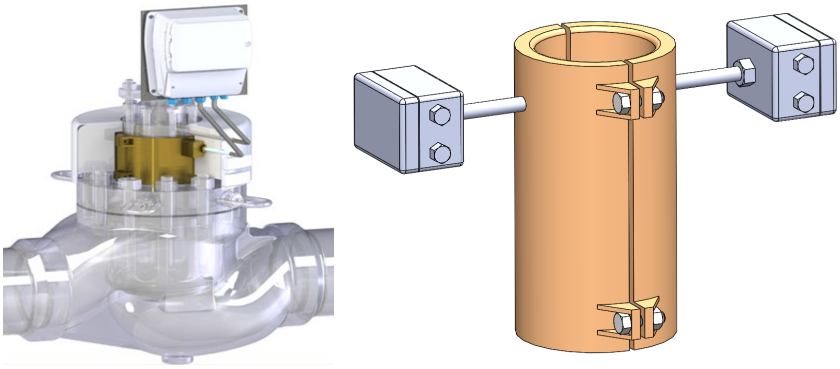


Figure 2. *Depiction of the STM (Thermal Management System).*

1.3 Heat Pipe Valve Stem

Design requirements were developed for valve stem heat pipe, several simplified steady state heat transfer models, which were created in Engineering Equation Solver (EES) based on the dimensions of a 2 NPS Flowserve Valtek Mark 1 Class 600 globe valve, Figure 3 with an extended bonnet for a ternary chloride salt [2]. Three different design configurations are under consideration including a bellows-sealed construction with a backup packing and self-contained thermal management (STM) sleeve around the bellows section, a quick-change packing only without a bellows and with the STM sleeve, and the potential inclusion of a valve stem heat pipe.

For the bellows-sealed configuration it was immediately clear that the introduction of a nitrogen gas gap between the valve stem and the bellows to counteract the pressure of the salt introduced a large temperature drop through the gas gap. This temperature drop could be reduced by replacing nitrogen in the gas space with a more thermally conductive gas like helium, but the temperature difference will still require a higher heat pipe operating temperature. More significantly, the STM sleeve in this configuration acts over a large surface area with the need to penetrate only 5/8" into the salt around the bellows and leaving little need for additional heat transport along the valve stem. This result is similar for the configuration without a bellows.

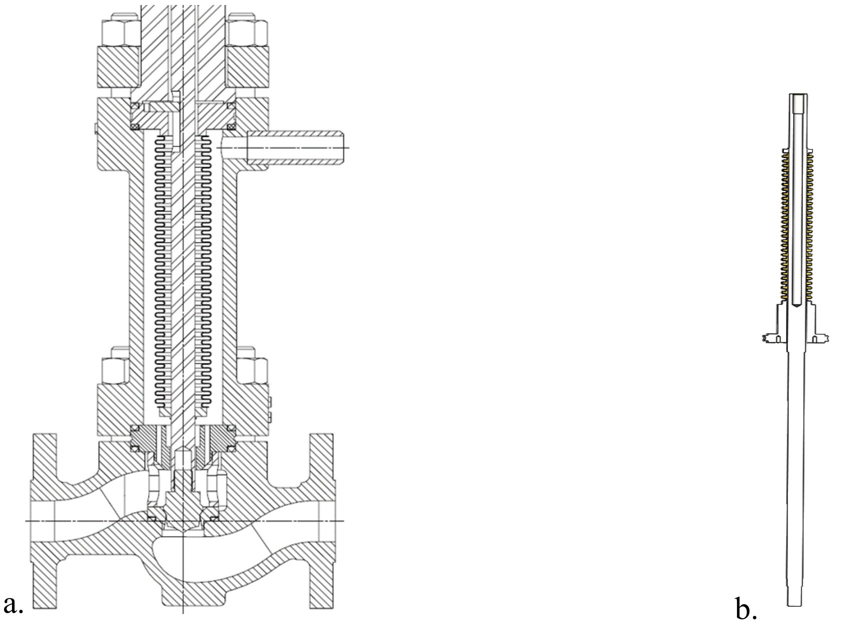


Figure 3. *Bellows-sealed valve a. cross-section and b. heat pipe valve stem.*

The designed bellows assembly consists of a Haynes 230 plug stem with Haynes 230 upper and lower fittings welded to the plug stem. The bellows consists of 3 plys, with two inner plys of Inconel 625 and an outer ply of Nickel 201. The outer ply of Nickel 201 provides the required corrosion resistance for the bellows assembly. When manufactured, the outer ply of Nickel 201 is peeled back, the inner plys of Inconel 625 are trimmed and seal welded to the Haynes 230 upper and lower fittings. The outer ply of Nickel 201 is then repositioned over the inner plys and seal welded to the fittings. Additional bellows options and testing under consideration for system design efficacy are:

- Perform corrosion testing on Nickel 201 seal welded to Haynes 230 to show that it meets the corrosion requirements.

- Nickel plate over seal weld and heat affected zone for added corrosion protection.

- Eliminate outer Nickel 201 ply and Nickel plate the entire assembly after welding.

For a valve configuration without the STM sleeve, a steady state thermal resistance network was created to represent parallel conductive heat transfer through the molten salt and pipe wall, up the valve stem heat pipe, salt-wetted packing, and valve bonnet, and finally through the top of the valve to an external heat source or yoke attachment for mechanical load transfer while accounting for external natural convection heat transfer from the surface of the insulation throughout the network. Due to the very low thermal conductivity of the chloride molten salt, the valve stem heat pipe will require an effective thermal conductivity on the order of 500 to 1000 W/m-K as shown in Figure 4; much higher than any standard metal and achievable only with a thermosyphon or pumped flow design. The wall heat flux and overall heat transfer duty is expected to be very low assuming reasonable insulation at between 50 and 100 W but given the small cross-sectional area available the axial heat flux 10^6 W/m^2.

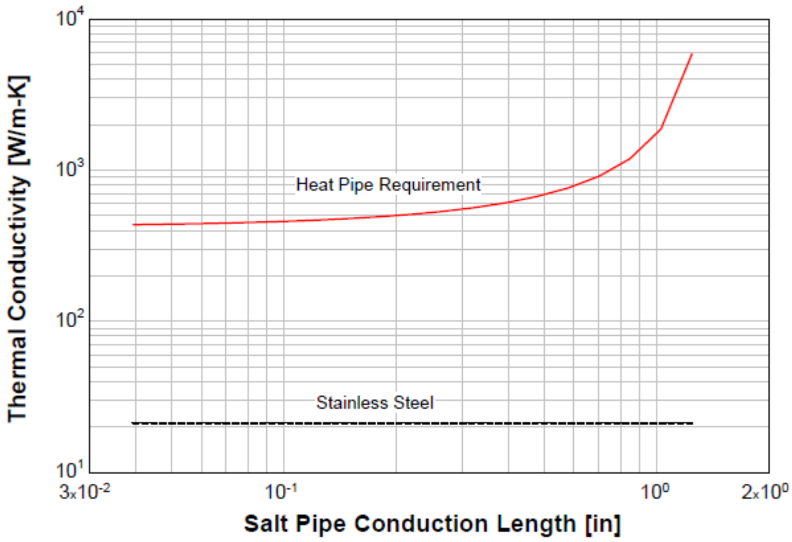


Figure 4. *Required valve stem thermal conductivity vs. salt conduction length to avoid freezing without the STM sleeve.*

2. Villach Test Loop Development

For our investigation, a high-temperature salt test loop was designed and fabricated to facilitate experiments of developed high-temperature prototype valves when used in chloride or fluoride salt up to 750°C. The system design, Figure 5, required focus on materials selection for Fatigue strength, Corrosion resistance and facilitating hot-leg and cold-leg piping operation at approximately 750C and 730C respectively. The system design also features a mobile support frame for flexible component changes, as well as a nitrogen ullage gas supply for bot the loop as well as the nitrogen gas purge ports in each of the valves tested. The design of the system would allow the control valves and attached flow sensors to modulate the flow coming from the salt pump, to then assess Cv and other flow characterization of the Test Valve. One should note that the control valves are an MK1 Flowserve model with an extended bonnet, that includes a quick-change packing configuration for added operational confidence and leak mitigation. Each section identified in Figure 5 above is defined as follows:

1. Heat tracing for pump and connection tubes in test loop (730°C)
2. Heat tracing for reservoir and the connecting pipes in test loop (530°C)
3. Heat tracing for main pipelines and valve bodies (730°C)
4. Heat tracing for bellows valve
5. Heat tracing for other potential test valves
6. Control panel for all heating systems
7. Ullage N2 gas system with connections to the valves, pump, and reservoir.

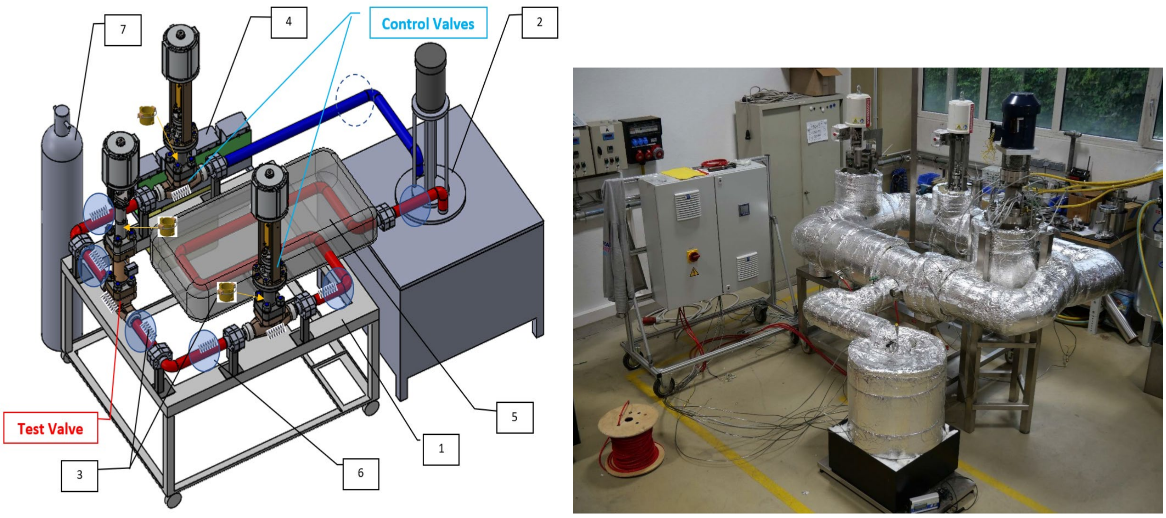


Figure 5. *Main components of salt valve test loop.*

Figure 6 shows a detailed view of the heat tracing and zones for the pump and connection tubes to the test loop. Also shown are the connecting tubes for water cooling of the mid-section of the pump.

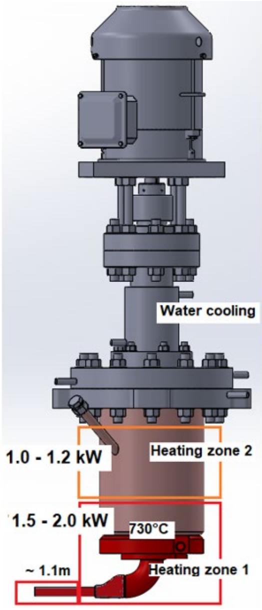


Figure 6. *Detailed view of heat tracing and zones for pump and connection tubes.*

It should be noted that the two zones help balance the heat loss upward through the pipe wall of the pump, and that the temperature setpoint is controlled via the thermocouples and control cabinets. Figure 7 shows a detailed view of the heat tracing for the reservoir and the thermal transport connections to the test loop. A spill tray surrounds the vessel where a weight scale is positioned underneath for assessing inventory.

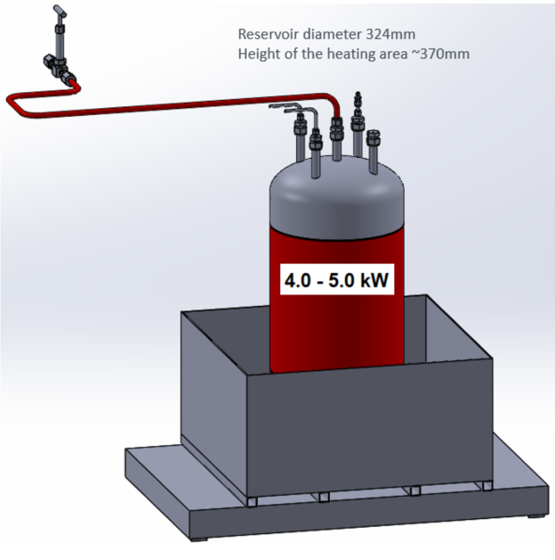


Figure 7. *Detailed view of heat tracing and zones for reservoir and connecting pipes.*

Figure 8 shows a detailed view of the heat tracing of the main pipelines and partial valve bodies, which includes the flanged connections, valves and the heating system, which inputs approximately 3.0 kW_{th} of thermal power into this portion of the thermal transport system.

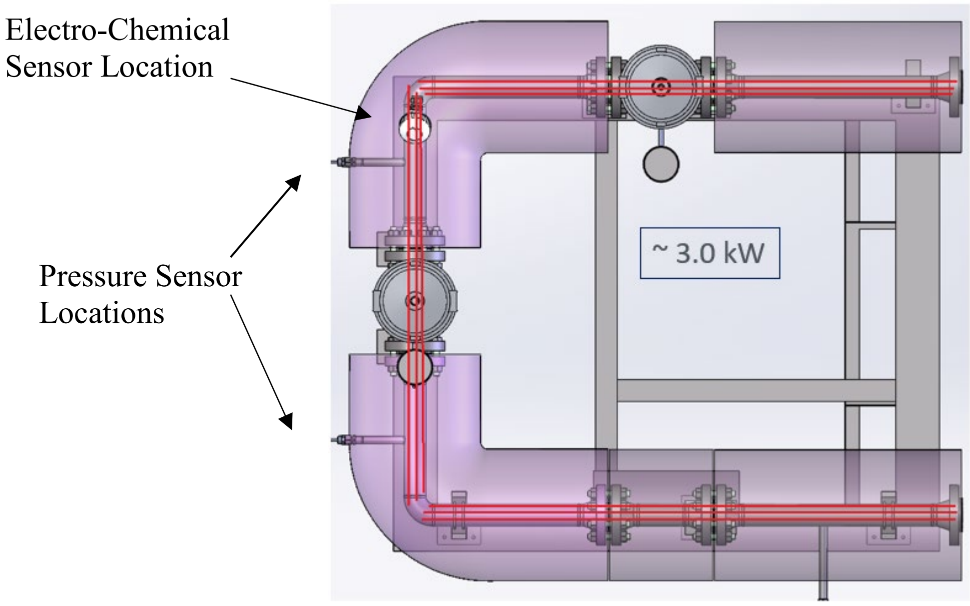


Figure 8. *Detailed top view of heat tracing of main pipelines and partial valve bodies.*

Figure 9 shows a detailed view of the heat tracing and multiple zones for the bellows valve and the quick-change packing valve. All heating systems are controlled through the control panel where the respective zones are shown in the figure, with an outline of the respective insulation zone shown in blue.

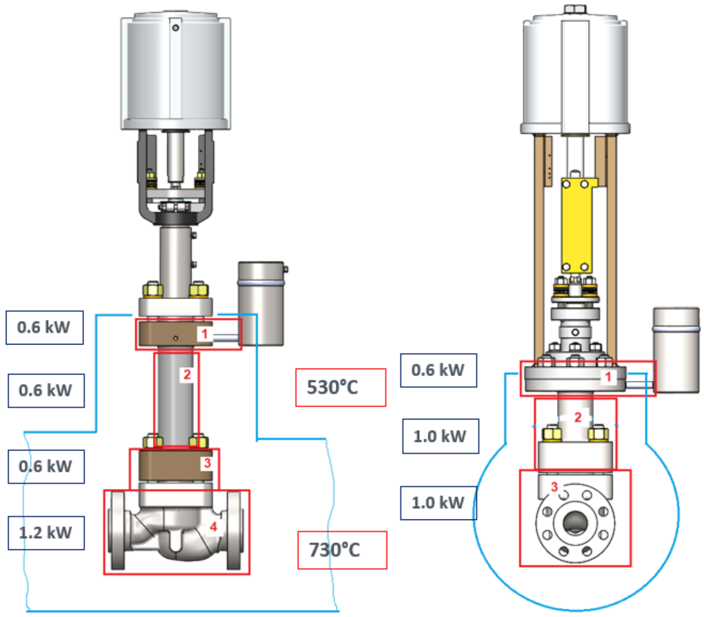


Figure 9. *Detailed view of heat tracing and multiple zones for test valves.*

Figure 10 shows the pump curve. This shows that the pump should deliver 10 GPM at 22.2 feet of head with an RPM of 35 Hz. This corresponds to the yellow curve in the figure below. Slightly higher RPM values represented by the grey curve should give higher flow. The flow rate is variable by changing the RPM of the pump.

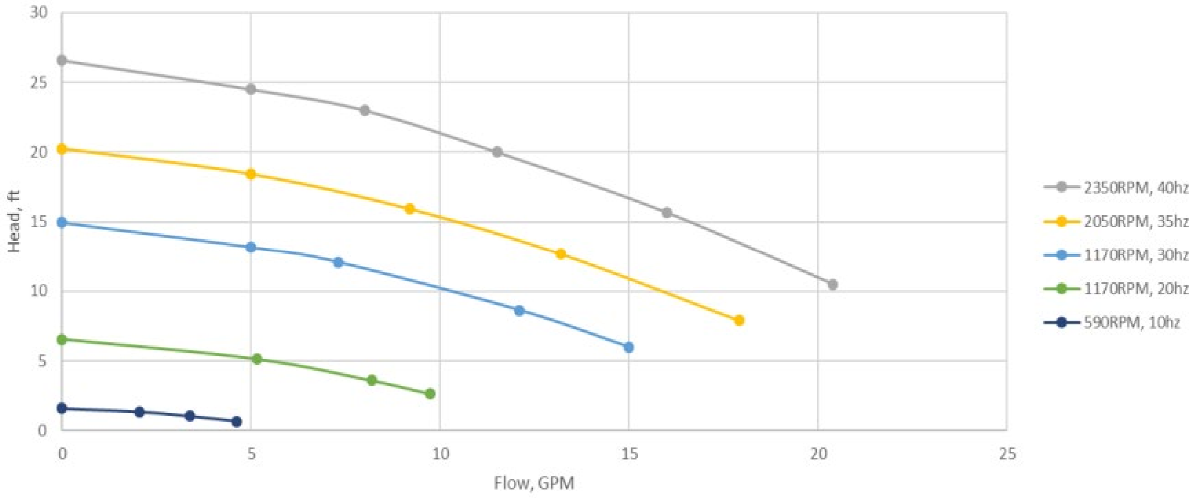


Figure 10. *Villach Test Loop Pump Curve.*

The pump curves for the test loop pump are based on 750 °C steady flow with the ICL purified ternary chloride salt with a density of 1.53 kg/m^3, and 1 bar of generated pressure (22.2' head). The curve is based on validated measurements with water for a similar pump with an identical impeller design. The pump construction is from Inconel 625. The curves are based on varying input frequency and subsequent RPM levels, between 590-2,350 RPM (10-40 Hz). The heat duty for the system is being calculated for the heat pipe based on an energy balance during varying flow operational modes of the valve, with heat input from the salt (at varying C_v values) and heater inputs. This analysis, which will be performed using the ANSYS Fluent CFD over the next quarter, will be based on the heat pipe geometry and level of sodium within the device. For the Villach test loop, heavy duty operation would be needed however for transient cases for freeze recovery and startup conditions while the system fills and to the same extent maintaining a minimum temperature while the system drains. Once the system reaches steady conditions, the duty cycle was found to be minimal to maintain a temperature of at least 530 °C.

3. Conclusions

A novel, advanced halide salt valve was designed and tested for reliable operation up to 750°C, for a 20%NaCl/40%MgCl2/40%KCl by mol. wt. % ternary chloride salt for CSP applications, with application capabilities for FLiNaK molten salt HTF for nuclear energy applications. The design featured STM active, and heat pipe valve stem passive thermal management systems to mitigate large thermal gradients, and to improve high-temperature operational performance and reliability. Two valves were designed, where a baseline FCV did not include the STM and heat pipe valve stem, which was tested at Kairos Power and found nominal performance, particularly after post-test materials inspections. The second, more advanced valve is planned for testing during the 2023 summer where post-test results analyses are expected to be completed by the 2023 SolarPACES conference.

Data availability statement

The data for this research work can be accessed directly from the authors.

Underlying and related material

Related materials can be obtained directly from the authors.

Competing interests

The authors declare no competing interests.

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