Molten salt flow control by passive float valve technique for solar thermal power application

By

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ABSTRACT

The steam generating (SG) system of 2 MW(e) Solar Thermal Plant, requires molten salt flow regulation inside it with the change in solar insolation which occurs during the day & night time resulting in temperature variation. To operate the solar plant in constant power mode, the molten salt flow rate from outer storage vessel to SG has to be regulated i.e. reduced flow during the day time and increased flow after the sun set. A passive flow control scheme using passive float valve (PFV) is being designed and developed for the molten salt flow rate regulation. Being passive it requires no/minimum operator action during its operation. Apart from robust design, zero maintenance, no power will be consumed for such flow control scheme. A concentric hollow cylindrical float with opening windows is conceptualised which will float around the outer periphery of the 450 NB SG chamber of solar plant. The SG chamber will also have desired window opening to allow the high temperature fluid to enter from storage vessel to SG. The molten salt flow from the storage vessel to SG will be controlled by the overlapping window area of the float and the SG chamber. The loss coefficient provided by the float at different level of the outer storage vessel has to be evaluated and matched with the requirements of the actual process for constant power operation. A cylindrical hollow float made of 1 mm thick plate of SS-304 material, having 460 NB inner cylinder diameter and 505 NB outer cylinder diameter with 300 mm height and 100×100 mm window is fabricated and tested in an experimental facility with water medium. Series of experiments were performed to generate flow characteristics of the designed float valve using forced flow by a pump. The controllability patterns of PFV have been generated by rotating the float from its 0 % to 100 % window opening at a constant water level. The size optimization of float window has also been done based on the flow rate characteristics. A high temperature natural circulation based experimental loop has also been designed with silicone oil as medium to simulate molten salt used in solar power plant.

This paper mainly deals with the development of passive flow control scheme using a 1:1 size float valve in water medium. The arrangement of steam generator, receiver and evaporator is brought out in the paper to illustrate the need for flow regulation. The design calculation, experimental results of float valve in water medium and methodology of float window size optimization based on the controllability patterns are also discussed.

Keywords: Solar Thermal Power, Natural circulation, Passive Flow Control, Float Valve, Float Window, Loss co-efficient.

1.0 INTRODUCTION

As a maiden demonstration of solar thermal technology in India, a 50 kW (e) solar thermal power project is proposed to be set up at BARC. Beam down technology with central receiver concept [1] has been adopted for the solar thermal power plant.

In this technology, a large hyperbolic reflector, mounted on top of the tower, reflects the solar radiation coming from the heliostats downward to the central receiver module. The central receiver module consists of receiver, steam generating (SG) chamber and storage vessel. Molten nitrate salt (60% $NaNO_3$ and 40% KNO_3) is used as the primary coolant in the solar power project due to its higher boiling point, on account of which system need not be pressurised even at high operating temperatures. Also molten salt has lower melting point, better thermal conductivity and heat capacity values. Concentrated heat flux i.e. solar insolation is applied at the top of receiver panel which is slightly inclined to favour natural circulation. After heating, molten salt goes to storage vessel through riser pipes and passes through SG chamber (which consists of evaporator and super-heater) located at the outer periphery of the storage vessel. The heat is transferred to water to produce steam for secondary cycle. Thermal storage of approximately 16 hours has been provided for continuous power supply during non-solar hours.

2.0 MOLTEN SALT FLOW REGULATION

There is a need of molten salt (primary coolant) flow regulation inside the receiver module of the solar power project for constant power operation. Molten salt flow has to be regulated due to the variation in solar insolation which occurs due to day-night temperature difference. Solar insolation in regions varies throughout the day in a contrasting manner. Solar insolation values are higher during the daytime (peak at around 14:00 hours during typical summer day) as compared to the night time. The heat transferred to the water for steam generation is given by the following equation;

$$Q = \dot{m}\, C_p\, \Delta T \quad \text{.............Eq. (1)}$$

To operate the solar power plant in constant power, the heat transferred to the water (Q) has to be constant throughout the day. Hence the molten salt flow rate from Receiver to SGS has to be lower during the day-time (when ΔT is maximum) as against the night time operation (when ΔT is minimum).

3.0 PASSIVE FLOW CONTROL MECHANISM

A passive flow control scheme has been designed for the molten salt flow regulation [2]. Minimum operator action is required during its flow control operation with zero maintenance. Apart from this, its design is very simple, robust and also no power will be consumed for such flow control scheme. A concentric hollow cylindrical float with window opening is conceptualised for molten salt flow regulation which will be submerged in the storage vessel and float around the outer periphery of the 450 NB SG chamber. There is a fixed window provided in the SG chamber to allow the hot molten salt to flow from the outer storage vessel to the SG. The float window will provide variable flow path to the molten salt liquid from the outer storage vessel to SG depending upon the temperature of the fluid, thereby providing variable resistance in the natural circulation loop to meet the constant power operation throughout the day.

4.0 CONCEPT OF PASSIVE FLOAT VALVE OPERATION

The passive float valve (PFV) concept has been proposed to control the molten salt flow rate based on the temperature of the coolant inside the receiver module. The float is expected to be submerged around the SG chamber and its position at a certain time of the day decides the flow resistance in the natural circulation loop. Change in temperature has contributed in both the change in level as well as change in density of the molten salt. Hence there are two factors which will decide the float position;

a) The level inside the storage vessel, L

b) The density of the molten salt, ρ_m

The float position at a certain temperature of the day will depend on both the factors.

$$\text{Float Position (m)} = f(L, \rho_m);$$

As the temperature increases, the level inside the storage vessel increases and the molten salt liquid density decreases. The change in level and change in density are governed by the following equations;

$$\Delta L = L(1 + \alpha \Delta T) \quad \text{………….. Eq. (2)}$$

$$\rho_{mT} = 2040 - 0.063 * T(in\ C) \text{… Eq. (3)}$$

Where

α : Thermal expansion coefficient of molten salt liquid in (cc/(cc-°C)

ρ_{mT} : Density of molten salt liquid at temperature T in kg/m^3

Hence with increase in level, the float will tend to go up, but at the same time due to the decrease in density, buoyancy force will decrease which will bring down the float. Hence the effective float position will be determined by the combined effects of the both level and density change of the molten salt. The float position at a specific temperature will decide the effective overlapping area between the float and SG chamber window, thereby ensuring the desired molten salt flow rate needed for constant power operation.

5.0 OPERATION OF FLOAT VALVE

During the daytime when both temperature and level inside the storage vessel is maximum, the natural circulation loop resistance has to be higher. Hence the float will be in such a position which will provide smallest or zero overlapping area with the SG chamber window opening (maximum resistance) and hence allowing minimum flow through the float valve. As the temperature decreases the level inside the vessel falls and density increases which will cause the float to effectively come down. Hence the overlapping area between the float and the SG chamber window, increases i.e. flow resistance reduces. This will lead to the higher flow rate through the float valve.

6.0 PFV DESIGN CALCULATION

In actual process, the float will be submerged in the storage vessel, around the outer periphery of the 450 NB SG chamber. For finalizing the shape, size and other dimensions of the float valve, basic force balance equation of a submerged body has been solved and a small computer program has been codded. A 1:1 size concentric hollow cylindrical shaped float with rectangular window opening has been primarily designed for the flow control scheme. The forces acting on the submerged cylindrical body is shown in Fig. 1.

The forces acting on the float body are as following:

F_W= Weight of the float

F_B= Buoyancy force

F_D=Drag force

Force balance equation can be written as

$$F_W = F_B + F_D \quad \text{……… Eq. (4)}$$

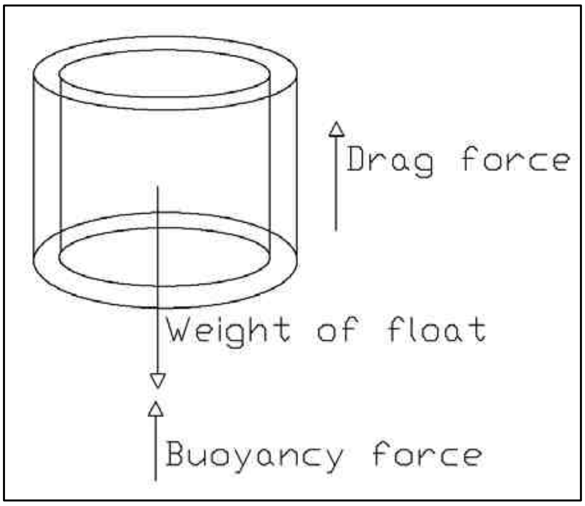

Figure 1. Force balance on the float

Where

$$F_D = C_d A_f \rho_m v^2 / 2$$

C_d : Drag co-efficient
A_f : Float area
v : Liquid velocity

At equilibrium condition, when the float becomes static, the drag force becomes irrelevant. Hence the force balance equation simplifies to

$$F_W = F_B$$

$$» \rho_f g V_F = \rho_l g V_d \quad \text{……… Eq. (5)}$$

$\boldsymbol{\rho}_f$: Float density in kg/m^3
$\boldsymbol{\rho}_l$: Liquid density in kg/m^3
V_f : Float volume in m^3
V_d : Displaced liquid volume in m^3

By balancing the forces acting on it, the float dimensions can be fixed. Once the dimensions are fixed based on the change in level and change in liquid density, the float position will be calculated.

7.0 PFV DESIGN FOR WATER MEDIUM

A float valve has been designed & developed for an experimental set up with water as the liquid medium. Only change in level is simulated in the experimental set up by manually changing the tank level. The float shape and size has been considered as 1:1 scale with actual SG chamber of Solar Power Project. The float is made of SS-304L material and consists of two concentric hollow cylinders. Float dimensions have been given in the Table-1.

Table-1: Float valve dimensions

Float material	SS-304L
Float shape	Hollow Concentric Cylindrical shape
Float density, ρ_f	7.94 kg/m^3
Float Inner cylinder diameter, r_2	460 mm
Float outer cylinder diameter, r_1	505 mm
Float material thickness, t	1 mm
Float height, h	400 mm
Float window shape	Rectangular
Float window size, (a × b)	100 mm (Horizontal) × 100 mm (Vertical)

For its construction, SS TIG welding was used for sealing its two ends by a 1 mm thick SS plate. Two numbers of rectangular window openings of 100 mm (horizontal) × 100 mm (vertical) size were provided in the float. The gap between the float and the 450 NB pipe was kept very minimal to allow the minimum required flow through the windows during the daytime and as well as to confirm the free movement of the float around the SG chamber.

8.0 EXPERIMENTAL SET UP

Experiments were conducted to demonstrate the float valve concept and to evolve its flow characteristics with the change in water level. For design validation of PFV, Phase -1 experimental set up has been designed, fabricated and commissioned, with water as flowing medium. An outer tank of 1.2 m× 1 m × 1 m size has been fabricated. A 450 NB, SS pipe has been installed in the centre of the tank whose shape is in 1:1 scale as the SG chamber to be used for solar power project. A SS float valve has been fabricated as explained in previous paragraph, to float around the 450 NB pipe and to control the liquid flow rate. Fixed windows are provided in the inner vessel matching with the float window. The experimental set up schematic diagram has been shown in Fig. 2.

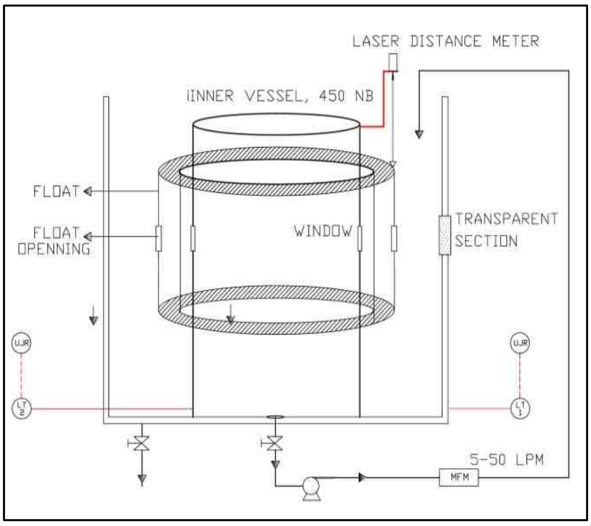

Figure 2: Schematic diagram of experimental set up.

A pump with 30 lpm discharge flow is used to generate the flow characteristics of the passive float valve. The pump suction is taken from the inner 450 NB pipe and water is discharged back to the outer tank. This is to establish closed loop circulation in the process. Pump flow rate is measured and monitored by the magnetic flow meter connected in the discharge line as shown in Fig. 2. Level transmitters are connected to the both inner and outer tank to record the decrease in inner tank level when pumping is in progress. An experimental set up as shown in Fig.3 & Fig.5 developed was developed.

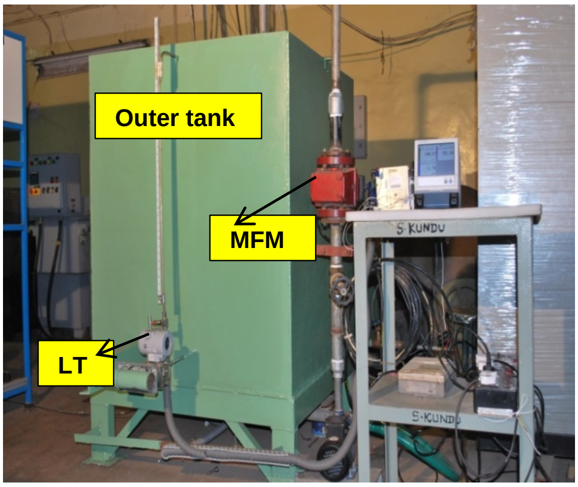

Figure 3: Passive Float Valve (PFV) experimental set up

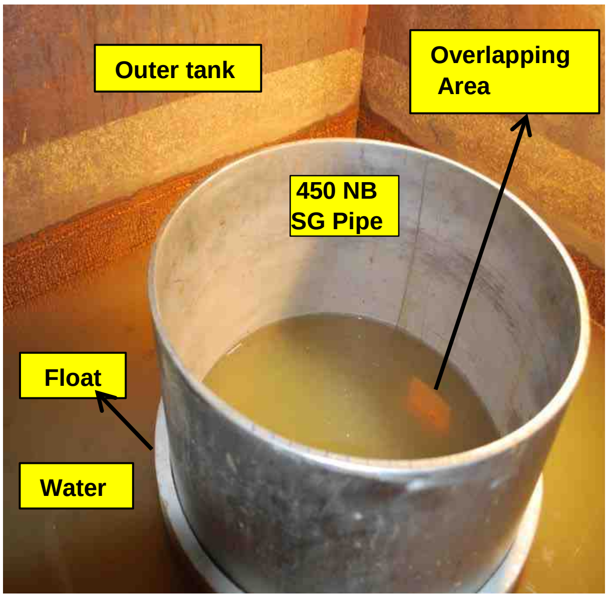

Figure 4: PFV floating around the outer periphery of the 450 NB pipe.

9.0 RESULTS

Experiments have been conducted to observe the float behaviour in the water medium and to study the flow characteristics through the float opening.

During the experiments it was found that float was moving upwards and downwards smoothly with 88% immersion in the water medium. Further experiments were performed to generate the flow characteristics of the float valve by rotating the float in small increments to obtain different window overlap, which gives various controllability patterns. With the Pump in ON state it has been found that the flow opening area of 100 X 100 mm size is providing very negligible resistance to the circulating flow. The float with the maximum slot size i.e. (100×100) mm basically acts as the quick opening valve where flow rate through the valve saturates after 20% of maximum opening. Hence the windows area was optimized from the initial experiments by rotating the float manually. Based on the controllability patterns of the float valve, experiments were performed with window opening of ‘X’ × 5 mm size (fixed 5 mm opening side wise) and ‘X’ × 10 mm size (fixed 10 mm opening). Therefore with 5 mm opening and 100 mm water level variation (850 mm to 750 mm) effective window (float) opening area of 0 to 500 mm^2 was obtained for ‘X’ × 5 mm window and 0 to 1000 mm^2 was obtained for ‘X’ × 10 mm window. Flow rate through PFV was measured by recording the change in the level inside the inner tank when pump is in ON & OFF condition. The effective level difference between the inner tank and outer tank is used for flow rate calculation through the float window. The flow rate calculation procedure is described below:

Let the Pump is in OFF state.
Let, Water level in both the Inner tank is L cm.
The amount of liquid present in inner tank per incremental level (cm) = $(\pi*0.45^2/4)$ = 0.159 litre/cm

With complete mismatch between float and inner vessel window i.e. 0% overlapping area, the level inside the inner tank after 1 minute of pump operation= L_1 cm.
And with the presence of float window the inner level tank level is L_2 cm after 1 minute of pump operation.

So the total flow rate through the float window = $(L_1-L_2)*0.159$ lpm.

From the experiments, the flow rate through the float window has been calculated at different level in the tank. For a window size of 100 mm (vertical) × 5 mm (fixed horizontal) size, the obtained float valve flow characteristic is shown in the Fig. 5.

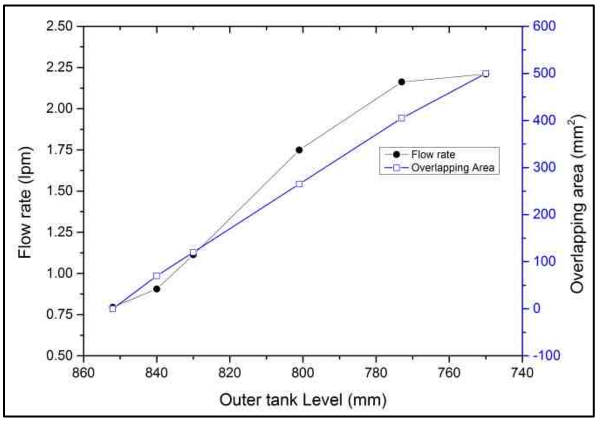

Figure 5: Float valve flow characteristics for 100 × 5 mm window

As shown in the Fig. 5, with a change in water level from 850 mm to 750 mm, the flow through the float window increases from 0.8 lpm to 2.25 lpm. This implies that at maximum level, the overlapping area is minimum which results in minimum flow rate and vice versa. Flow characteristics of PFV also suggests that 100×5 mm window size has an active flow regulation zone in between 100-400 mm^2 of float opening area. It is observed that after the flow regulation zone, the flow rate through the PFV tends to saturate.

For a window size of 100 mm (Vertical)× 10 mm (horizontal) size is also evaluated and the results are shown in the Fig. 6;

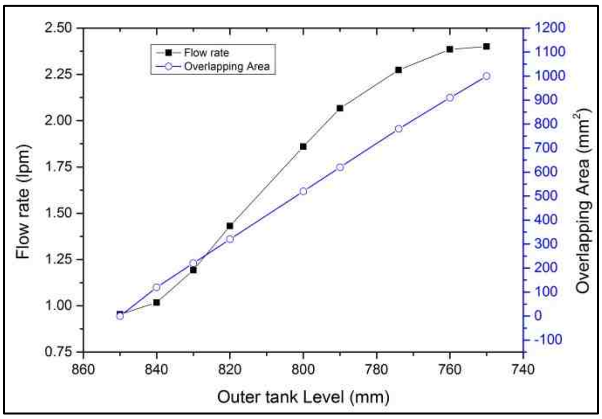

Figure 6: Float valve flow characteristics for 100 × 10 mm window

From the Fig. 6, it is observed that the flow opening area has been increased and flow rate through the window slightly increases. The flow rate through the 5 mm horizontal fixed window at 800 mm water level is found to be 1.75 lpm whereas for 10 mm fixed window it increases to 1.87 lpm. However for a 10 mm fixed horizontal window the flow regulation zone increases to 50-800 mm^2.

10.0 NATURAL CIRCULATION BASED PROPOSED SET UP

Based on the passive float valve data in earlier experiments, a high temperature natural circulation based experimental set up has been designed to study the float performance in silicone oil medium [3]. In this both the level and density of the liquid changes simultaneously due to heating. The setup has been designed to match with the actual solar thermal power plant process. Silicone oil is selected as high temperature liquid to be used in the experimental loop at 150°C. The density of the selected liquid is also almost same as water i.e. 965 kg/m^3 at 25°C. The density variation of silicone oil is found to be 120 kg/m^3 for a temperature change of 125°C i.e. 25 to 150°C.

The experimental set up consists of one outer vessel (storage vessel) of 750 mm (L) X 750 mm (W) X 600 mm(H) size made of SS-304L material. Inside the outer vessel a 1:1 shape and size inner vessel (equivalent to SG chamber) of 450 NB diameter and 600 mm height will be installed. There will be fixed opening provided in the Inner vessel to allow natural circulation in the process. At the bottom of the inner vessel, 1'' SS pipe down-comer line will be connected with flow meter and inclined riser pipes will be further connected back to the outer vessel. The inclined riser pipes will be heated by the band heaters for establishing the natural circulation in the system. The designed passive float valve for the silicone oil is made of SS-304 material, having a size of 460 mm inner cylinder diameter and 520 mm outer cylinder diameter. The float will be placed around the outer periphery of the inner vessel. The float will have variable window opening through which liquid (silicone oil) can flow to the inner vessel depending on the overlap area of the float window and inner vessel fixed opening. A cooling coil made of ½ inch SS tube is placed inside the inner vessel to remove the heat from the hotter liquid. The detailed drawing of the experimental set up is shown in the Fig. 7.

The natural circulation in the loop will be established by heating the 1'' riser pipe. As the heating starts, the relatively hotter liquid will go up and enter the relatively cooler zone of the inner vessel through the overlapping opening area between the float and inner vessel window. Heat will be extracted from inner vessel by cooling water recirculation line. The heat removed from the inner vessel will ensure a natural circulation in the system. As the temperature increases the density of the liquid decreases and level rises due to thermal expansion. With rise in level float will also go up but due to decrease in density the float will try to immerse more.

Hence the combined effect of the simultaneous change in liquid level and density will decide the float position. The overlapping area of the float window and inner vessel opening will reduce with the temperature increase. In other words the float valve will close more. The float valve area is optimised such that at lower temperature when the natural circulation flow (in night time) is minimum, it will provide maximum opening and hence will allow maximum flow-rate.

The heater power will be measured experimentally during the experiments as well as temperature at heating zone inlet and down-comer outlet will be measured to calculate the flow rate in the natural circulation loop. Also the cooling water flow rate, its inlet and outlet temperature will be measured during the experiments.

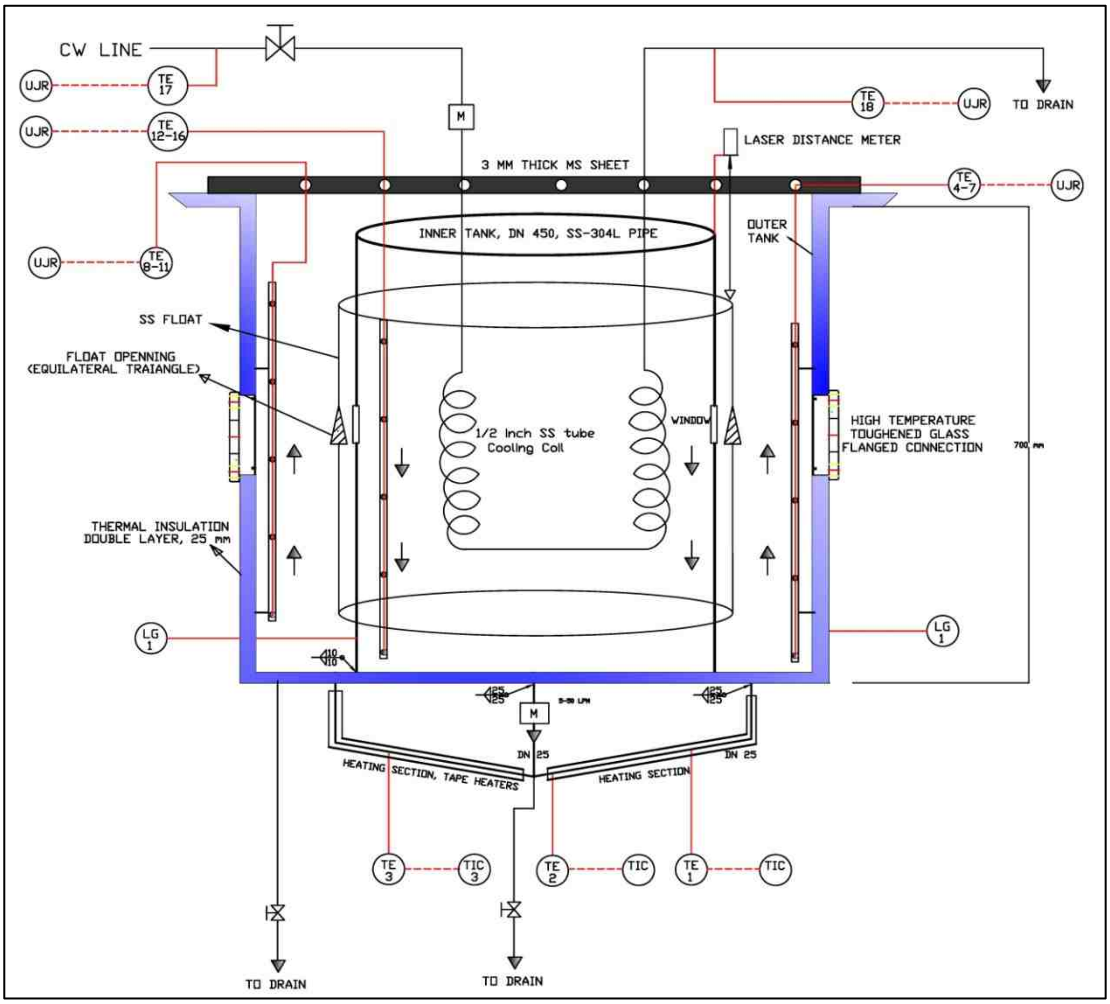

Figure 7: Natural circulation based Passive Float valve experimental set up

As the temperature goes up (in day time), the natural circulation flow increases, but due to lesser overlapping float area, the flow-rate will be reduced. The details of the experimental set up are given in the Table-2

Table-2: Dimensional details of experimental set up

	Parameters	Size
Float, SS-304L		
	ID	460 mm
	OD	526 mm
	Wall thickness	1 mm
	Float window	Inverse triangular shape
Outer vessel, SS-304L	Length	750 mm
	Width	750 mm
	Height	600 mm
	Window	20 X 20 mm rectangular shaped
Inner vessel	Diameter	450 mm
	Height	750 mm
	Wall thickness	8.77 mm

11.0 EXPECTED OUTCOME OF THE EXPERIMENTS

From the above experiment we will generate the loss co-efficient value of the designed float for the inverse triangle shaped window. With the change in temperature as the level changes the float window relative position changes. Hence by calculating total resistance provided by the float, the area can be optimized and extrapolated for the actual application with molten salt.

A preliminary calculation has been done for the above high temperature loop [4]. The relationship between the float relative positions with temperature is established. The overlapping area between the inner vessel window and float opening at different temperature will determine the loss co efficient of the loop for controlling the flow rate of the liquid. The following equations are needed to be solved for calculating the loss co efficient of the float valve:

Driving force=Total resistive force in the loop

$$F_d = F_r$$

$$\text{»}\ \Delta\rho g H = \left(\frac{\sum\left(\frac{fL}{D}\right)\rho V^2}{2}\right) + \sum\left(\frac{K\rho V^2}{2}\right) \quad \text{…Eq. (6)}$$

Where,

- H : Height difference between hot section and cold section
- L : Equivalent pipe length
- D : Equivalent pipe diameter
- K : Total loss co-efficient due to pipe bend, expansion and contraction in pipe.

By solving the above equation, the natural circulation velocity, V, or mass flow rate, Q_m, of the closed loop system can be calculated. To calculate the float position at different temperature below equations has to be solved:

Rise in level: $\Delta L = (\frac{\Delta\rho}{\rho_{25}})L$ ……. Eq. (7)

Buoyancy force = Weight of the float

$$\rho_l v_l = \rho_f v_f \quad \text{……….Eq. (8)}$$

By solving Eq. (7) & (8) we can get the percentage of immersion for the float at different temperature, thereby the relative position at different temperature can be calculated. After solving the above equation for the designed float the relative position of the float w.r.t inner vessel window has been calculated and plotted against the temperature.

For our designed float, the position of float valve has been theoretically calculated and the estimated float position vs. silicone oil liquid temperature graph has been shown in Fig. 8. It has been calculated that at minimum temperature of 25 °C the float position with respect to the inner vessel window is such that it gives 100% overlapping. Hence at lowest temperature the resistance seen in the loop will be minimal. As the temperature goes up the relative position of the float decreases and when it reaches maximum temperature of the loop (150 °C) the overlapping area is almost minimal (around 10 %) thereby providing maximum resistance in the loop which will ensure minimum flow rate from outer vessel to inner vessel. Thus by measuring the flow rate at different temperature we can find out loss co efficient values contributed by the float

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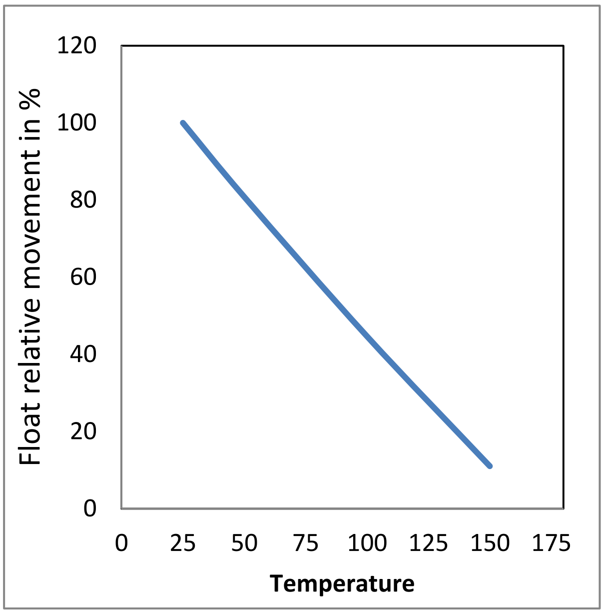

Figure 8: Float relative position (theoretical prediction) w.r.t, temperature of the primary coolant (Silicone oil).

12.0 CONCLUSION

The float valve designed for the solar application can control the molten salt flow rate completely by passive means without any need of operator intervention. The two concentric hollow cylindrical shaped SS float valve has been designed for this application. The float valve is successfully tested and demonstrated in the water medium and experiments were carried out for generating the flow characteristics. With water medium the float valve is exhibiting a flow regulation zone of overlapping area of 100-400 mm^2 with 100 mm (vertical) X 5 mm (horizontal) sized rectangular window. The flow regulation zone increases to 50-800 mm^2 for 100 mm (vertical) X 10 mm (horizontal) sized rectangular window. A high temperature natural circulation based experimental loop has been designed to study the float valve performance in silicone oil medium wherein the liquid level and density, both changes with the process temperature at the same time. Also to counter the low flow velocity of the liquid in lower temperature, the window shape is modified to inverse triangular shape. The area of the inverse shaped triangular window keeps on increasing as the float comes down along with level, thereby compensating the lower liquid velocity.

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