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EXPERIMENTAL INVESTIGATION ON CHILLDOWN ENHANCEMENT ALONG ALUMINA COATED SPHERE PACKED SS REGENERATOR

Shanu O S[1], Abhiroop V M[1,2] & Reby Roy K E[1]
[1]Department of Mechanical Engineering, TKM College of Engineering, Kollam, India
[2] Department of Mechanical Engineering, Marian Engineering College; Thiruvananthapuram, India

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ABSTRACT
To optimize the cryogenic regenerator and to improve the efficiency of the cryogenic systems, chill down time should be less. Time-saving is related to saving of consumption of cryogenic fluid. An experiment was performed to evaluate the modification and enhancement on the quenching heat transfer by a nanoporous heat transfer matrix, with that of a regenerator with non-coated matrix. Experiments were performed on spherical bed SS regenerator with alumina coating on the matrix at different inlet pressures. The stainless steel balls were packed to a porosity 0.6 to make the matrix. Alumina is coated on the spherical bed by Sol-gel dip coating method with Aluminium isopropoxide as the precursor. Liquid nitrogen is used as the cryogenic fluid. The performance of the regenerator with uncoated and coated matrix at corresponding pressures were compared. The results indicated that there are substantial savings in the chilldown time with coated bed compared to the non-coated bed regenerator. The significant reduction in chilldown time is observed only after the arrival of the nucleate boiling region as depicted from the average surface temperature versus time graph

KEYWORDS: Regenerator, stainless steel spheres, alumina, chilldown.

1. INTRODUCTION
A regenerator is a heat exchanger consisting of a thermal mass or matrix which acts as a storage medium for heat. It is characterised by low volume to the surface area which enables higher heat transfer characteristics for a given amount of volume. Materials with low thermal conductivity and high heat capacity are used for the fabrication of regenerators. Use of low thermal conductivity materials facilitates the reduction of axial conduction in the regenerator matrix. The thermal performance of regenerator can be improved by increasing regenerator bed size or by coating the material with a low thermal conductivity material. However, increasing the bead size may lead to a significant pressure drop. By considering these two factors, the regenerator bed size, as well as its properties, will vary for different applications. Regenerators are of two different types namely, rotary matrix type and fixed matrix type. In rotary regenerator the fluid flow direction remains same while the matrix rotates. In fixed matrix type regenerator intermittent flow of hot and cold working fluid occurs through the same matrix.

Regenerators find wide application in the field of cryogenics. They are used in liquefaction systems, pulse tube, active caloric cooling systems and also find application in space technology. At cryogenic temperature, the specific heat of a material is lowered. So cryogenic regenerator bed size will be larger compared to the regenerators working in near room temperature for a given heat load. Many irreversibilities are associated with the performance characteristics of regenerators. Pressure drop is one of the significant irreversibility related to fluid flow through packed beds. Ergun's equation gives pressure drop for flow through matrices of spherical particles. Sodr et al. [1] developed a model to predict the pressure drop for flow through an annular packed bed of spheres at random distribution. He used Ergun's equation with corrected flow velocity to predict the pressure drop and was in good agreement with experimental values. Pamuk et al. [2] studied the heat transfer experimentally in porous media under oscillating water flow. He proposed a more general Nusselt number

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correlation independent from the type of porous medium and fluid properties. Pamuk et al. [3] also made another study on friction factor, permeability and inertial coefficient of oscillating flow through porous media of packed balls. Rout et al. [4] have worked on the influence of porosity values of regenerator on the performance of pulse tube refrigerator. He used wire mesh as the regenerator matrix and observed that the porosity values of 0.6 are optimum for the pulse tube regenerators.

2. EXPERIMENTAL SETUP

The set up consists of Gaseous Nitrogen cylinder, Liquid Nitrogen Dewar vessel, pressure regulator, valves, Data Acquisition system(DAQ), pipes and brass fittings, electric heater, flow meter and the test section. Figure 1 shows the schematic of the experimental setup used. The test section is made of stainless steel of dimensions 12.5mm (outer diameter), 11.3mm (inner diameter), 50.1mm (length). Thermocouples were placed at three different positions from the inlet for measuring the outer wall temperature and. The outer surface and spherical matrix of the regenerator is coated with nano-alumina by a sol-gel dip coating method using Aluminum isopropoxide as aluminium precursor and acetic acid as hydrolysis rate controller and DI Water as solvent [7]. The heat in-leak to the test section was minimized using a thick layer of nitrile rubber insulation with a lower thermal conductivity value (0.03W/mK). The test section was also covered by yarn and then by Nitrile rubber insulation. Liquid Nitrogen is supplied to the test section through 1/2" SS 304 grade pipes and brass fittings from a 55L Dewar made by IBP Co. Limited (TA-55). The liquid nitrogen was pumped from Dewar vessel by external pressurization using a gaseous nitrogen cylinder. The flow rate of liquid Nitrogen is manually regulated by a pressure regulator mounted on the external pressurization line. Initially, the entire test setup is purged with gaseous nitrogen. A by-pass line is introduced to ensure the entry of saturated LN2 into the test section. Temperature measurement of the test section was done using T-type thermocouples connected to Keysight 34972A data acquisition/data logger switch unit with a scan frequency of 30 milliseconds which is connected to the personal computer for data analysis. The average mass flux was measured using a volume flow meter, having an accuracy of 0.05 mm3/s at the exit line from the test section. Single phase flow meter is provided, which is used for measuring flow rate. To ensure single phase gas flow entering the flow meter, the outlet line is placed in a hot water bath heated by electric heaters. A pressure gauge is provided for measuring and regulating initial pressure.

Stainless steel spheres of uniform diameters are used as the thermal mass of the regenerator. Figure 2 indicates the physical arrangement of spherical balls within the regenerator with uncoated and coated spherical bed matrix. The porosity of the regenerator bed is the ratio of total void volume to total volume. The porosity of the regenerator used in this experimental study is 0.6. Experiments were conducted for three fixed mass flow rates (2.292g/s, 2.813g/s, 3.33g/s) corresponding to three different inlet pressure (7.5psi, 10psi, 12.5psi) conditions. The equation for finding effectiveness (e) can found in work done by Behery et al. [8]. The test specimen is positioned in a horizontally to reduce the effect of gravity in the chilldown process.

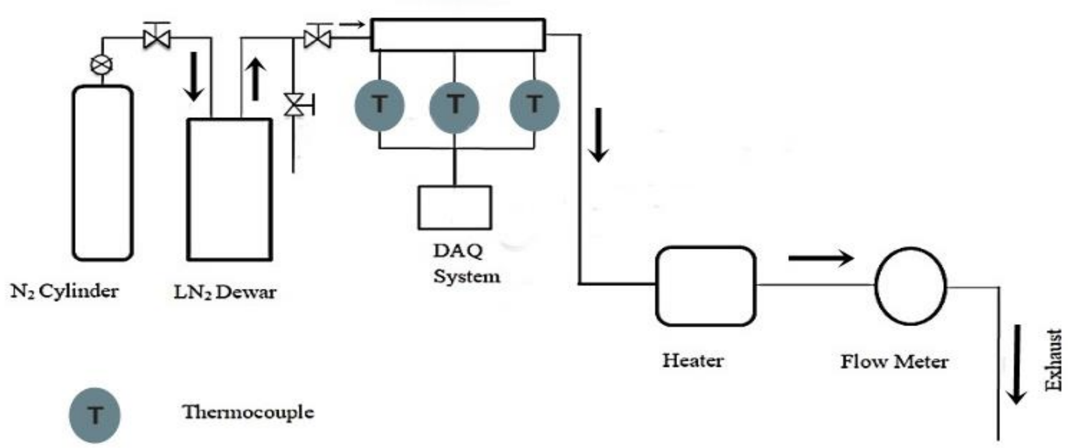

Figure 1. Schematic of experimental setup

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The equation (i) for finding effectiveness (e) can found in the work done by Behery et al. [8]

$$e = \frac{(mC_{p_a}T_{ca} - mC_{p_h}T_{ch})}{((mC_p)_{min}(T_c - T_h))} \text{(i)}$$

Where m is mass flow rate, Cp_a is mean average specific heat, T_{ca} represents mean average temperature, Cp_h is the specific heat of hot fluid, T_h is temperature of hot fluid and T_c is temperature of cold fluid.

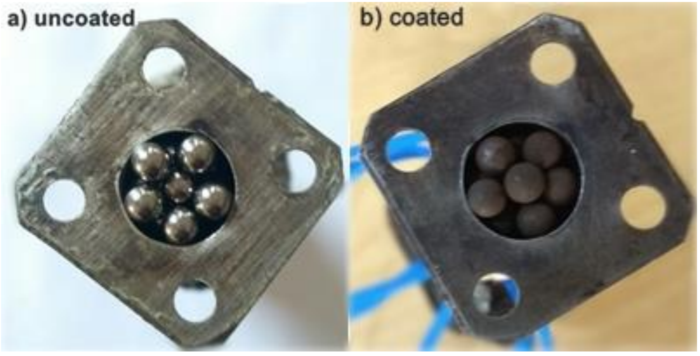

Figure 2. Regenerator filled with (a) uncoated and (b) coated ss spherical balls

3. RESULTS AND DISCUSSION

The temperature-time profile of a chilldown process can be divided into three regions, which will have a constant temperature gradient, a sudden temperature drops and constant temperature region. The first region refers to the film boiling regime where the flow structure could be inverted annular or stratified flow. The second region represents the transition boiling region where the wall temperature drops suddenly, and the third region is a nucleate boiling regime where the flow will be bubbly or slug discharge. But in the present work, the chilldown characteristics differ from the standard boiling curve due to the spherical bed geometry.

The chilldown time varies with the mass flow rate along the regenerator bed. Figure 3 shows the chilldown process in the temperature-time plot. Chilldown rate is faster for higher mass flow rates. At higher mass flow rates, there will a substantial increase in the thermal capacity of the flowing fluid, which leads to a rise in utilization factor. Figure 3b shows the plot for coated bed regenerator where the chilldown is much faster due to nano porous surface in the film boiling regime and the Increase in thermal capacity of working which fluid leads to removal of heat load at a faster rate which facilitates chilldown at the earliest. When mass flow rate increases, the transition from film boiling to nucleate boiling occurs at higher wall temperatures. The temperature distribution along the regenerator length varies along the length of the regenerator.Figure 4 shows the temperature at different positions of the test section. The dimensionless position expressed here is the ratio of the distance between the inlet and corresponding thermocouple position to a total length of the regenerator. It is to be noted that with the increase of mass flow, the utilization factor increases, which leads to a higher temperature difference between the initial and final state. This indicates constant temperature penetration at much higher rates to the regenerator matrix. From the plot, it may be noted that the temperature decreases along the regenerator from inlet to outlet. This decrease in temperature along the flow direction is due to axial conduction, which in turn leads to a significant reduction in effectiveness as referred by Trevizoli et al. [5].

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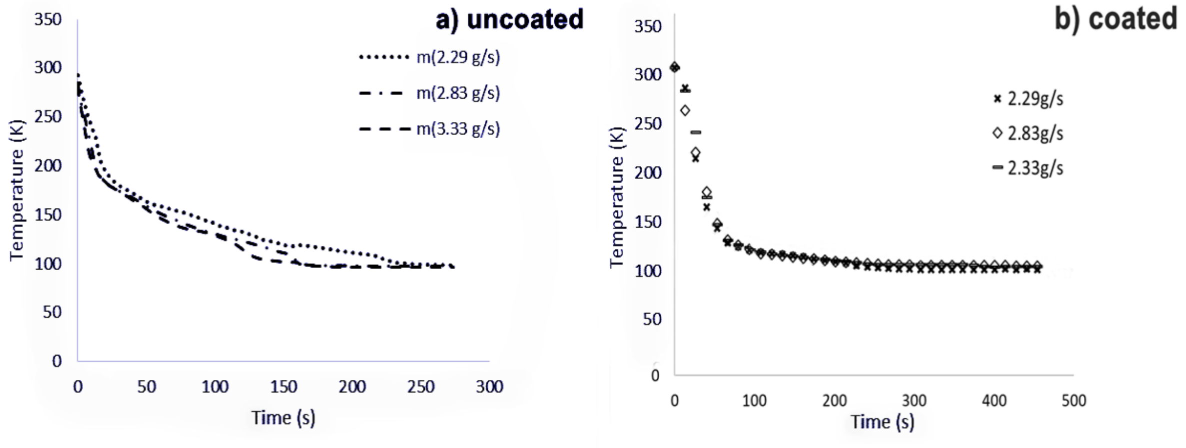

Figure 3. Temperature-time plots for (a) uncoated and (b) coated spherical bed specimen for different mass flow rates.

The normal matrix regenerator spent 243 seconds in chilldown while coated matrix took only 205 seconds to chilldown the regenerator under same inlet condition. There is an increase in heat transfer with an increase in the turbulence of flow at higher mass flow rates. Increase in mass flow reduces the wall and bulk temperature due to an increase in convective heat transfer between wall and fluid which leads to an increase in Nusselt number as observed by Pamuk et al. [2]. The excellent surface wet ability associated with these nanoporous surfaces has significant potential to enhance heat transfer. A slight increase in the temperature at mid-section (figure 4b) of the coated bed regenerator can be inferred due to the presence of backpressure at the initial stage.

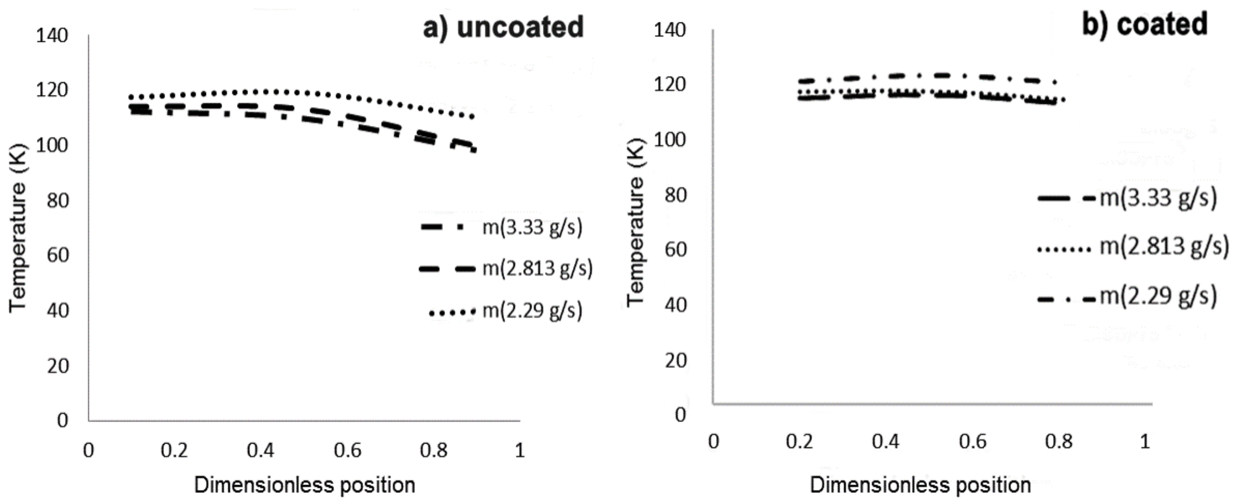

Figure 4. Temperature- Position plot

Increase in mass flow reduces the wall and bulk temperature due to increase in convective heat transfer between wall and fluid. This leads to increase in Nusselt number as observed by Pamuk et al [2]. As the temperature attained at outlet of coated bed specimen is less compared to the uncoated matrix type, higher the effectiveness for coated bed specimen.

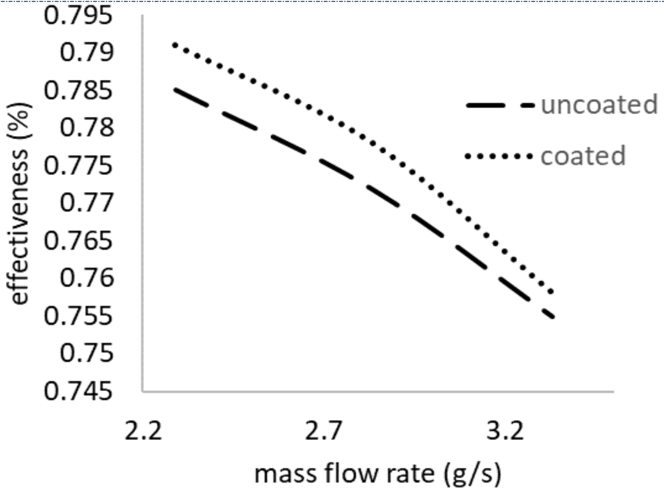

Figure 5. Effectiveness vs mass flow rate plot

The variation of effectiveness of the regenerator with an increase in mass flow rate is shown in figure 5. It is observed that the effectiveness of the regenerator decreases with an increase in mass flow rate. This is because, with the increase in mass flow, chilldown occurs at a much faster rate and temperature drop will be more. This is because, as heat capacity increases, the temperature change in fluid decreases and at low temperatures, the specific heat decreases. This leads to a reduction in effectiveness at higher flow rates.

4. CONCLUSION

The experiments were conducted to compare the chilldown characteristics of nano-alumina coated and uncoated fixed bed ss regenerator for different mass flow rates corresponding to three different inlet pressures (7.5psi, 10psi, 12.5psi). It was observed that the chilldown time is minimum for the maximum pressure condition in both the cases, also the coated specimen resulted in faster chilldown. The nanoporous surface has shown superiorphase-change heat transfer performance than the normal surface in all three boiling regimes. The effectiveness of the regenerator is found to be decreasing with increase in supply head in both the cases. The maximum value of effectiveness obtained is 0.792.

5. ACKNOWLEDGEMENTS

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