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CFD analysis for chill down along a packed spherical bed regenerator

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Abstract— Efficiencies of cryogenic systems are very low when compared with systems operating at higher temperatures. Efforts are required to improve the operating efficiency of cryogenic systems and thereby reduce the input power requirements. A large amount of power is lost along cryogenic systems due to chilldown process. The present work aims to improve the chill down characteristics along a spherical bed regenerator. The effect of porosity in a spherical bed generator is studied. Numerical simulations were conducted on a stainless steel spherical bed regenerator having porosities 0.4 and 0.5. The flow rate and other boundary conditions were kept constant for both the geometries. The CFD model was validated with the experiment data. Appreciable improvement in chill down was found with decrease in porosity.

Index Terms— *CFD analysis, Porosity, Spherical bed regenerator, cryogenic regenerator, effectiveness, liquid nitrogen*

1 Introduction

The efficiency of regenerative type cryocoolers depends on the performance of regenerative heat exchanger to a large extent. A regenerative heat exchanger is a sort of heat exchanger where heat from the hot fluid is intermittently stored in a thermal storage medium before it is transferred to the cold fluid [3]. These heat exchangers are made up of materials with high volumetric heat capacity and low thermal conductivity. Compact heat exchangers are characterized by a high heat transfer surface area per unit volume of the exchanger. Improved performance of compact cryogenic regenerative heat exchanger necessitates very good heat transfer between the fluid and the matrix with a low pressure drop [5]. However to improve the heat transfer, one normally has to pay with higher pressure drop [2]. Another parameter which influences the thermal efficiency is the longitudinal thermal conduction in the matrix, which should be small as possible. A complete three dimensional modeling and analysis of the matrix is essential for getting a deeper understanding of the principles behind the fluid flow and heat transfer in a regenerative heat exchanger. The present work involves the numerical analysis of fluid flow and heat transfer characteristics of a compact regenerative heat exchanger for cryogenic applications. Studies were conducted with a stainless steel spherical bed regenerator with two different matrix porosities (i) porosity of 0.4 (ii) porosity of 0.5. The change in porosities was obtained by changing the diameter of spherical balls. The widely used commercial CFD-package Ansys FLUENT is used as tool for the analysis. The CFD calculations are done to evaluate the chill down along the spherical bed regenerator and also to study the effect of porosity on chill down. Also the CFD model is validated with experiment results.

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2 Modeling and governing equations

2.1 Geometry

The regenerator considered for the present analysis is a spherical bed regenerator having l/d ratio of 4.43 and a wall thickness of 1.2mm. Stainless steel balls were used as regenerator matrix. Two different cases were simulated with porosities 0.4 and 0.5. The porosity is varied by changing the diameter of spherical balls so that d/D ratio was kept 0.1947 and 0.2805. Where d is the diameter of ball and D is the inner diameter of regenerator wall.

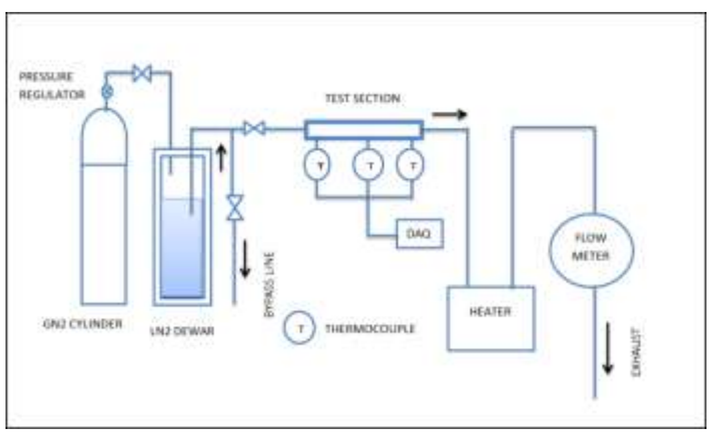


Fig. 2.1 Schematic of experimental setup

Fig. 2.2 Actual regenerator with porosity 0.6

Figure 2.1 shows the schematic diagram of experiment setup used [15]. The cryogen used for analysis is liquid nitrogen. Liquid nitrogen at 77K is allowed to pass through the regenerator. Initially regenerator is at ambient temperature. Figure 2.2 indicates the actual regenerator with porosity 0.6 and ratio of diameters 0.3319. The experiment results are discussed in our previous work [15]. In the present analysis mass flow rate of 3.33kg/s alone is considered for evaluating the CFD model.

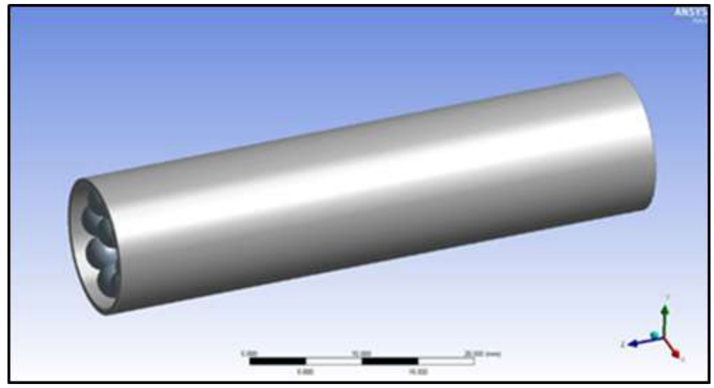
2.2 3D Modeling

The regenerators with porosity values of 0.4 and 0.5 were modeled in ANSYS design modeler. Meshing of the geometry is done by using Ansys Mesh software. Meshing is done with relevance centre as fine and smoothing of high is provided. Tetrahedral meshes were used in meshing. Orthogonal quality of above 0.82 was maintained for both the cases. Fig. 2.3 indicates the 3D model of the regenerator and Fig. 2.4 shows the meshed geometry for porosity 0.4.

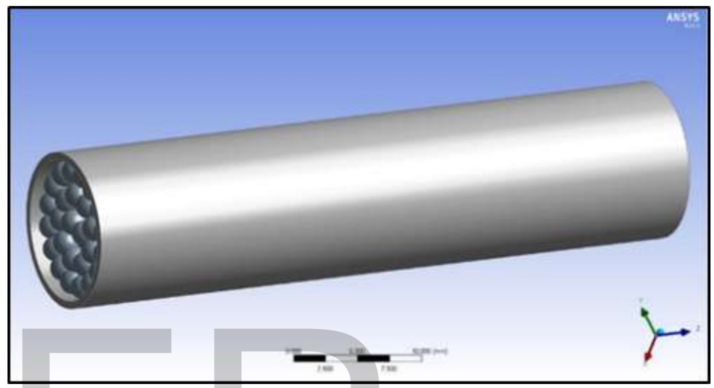
2.3 Boundary Conditions

The inlet boundary condition is specified as mass flow inlet and fluid temperature at inlet is assumed to as 77K. Saturated liquid nitrogen is chosen as working fluid. The outlet boundary condition is taken as the pressure outlet and it is assumed to be at ambient condition. The wall heat flux is taken as zero in the assumption that the regenerator is perfectly insulated. The turbulent intensity and hydraulic diameters were specified as 5% and 0.0113m respectively. The flow is assumed to be unsteady and fluid as incompressible, so pressure based solver is used for the numerical analysis. The SIMPLE (SIMPLE-Consistent) algorithm is used as the solution method. This algorithm is essentially a guess-and-correct procedure for the calculation of pressure on the staggered grid arrangement.

To initiate the SIMPLE calculation process a pressure field is guessed and the discretized momentum equations are solved using the guessed pressure field to yield the velocity components. The correct pressure is obtained by adding a pressure correction factor to the guessed pressure field. To avoid the divergence problem a suitable under relaxation factor is considered during the iterative process.



Porosity 0.4



Porosity 0.5

Fig. 2.3 Modeled sphere bed regenerator

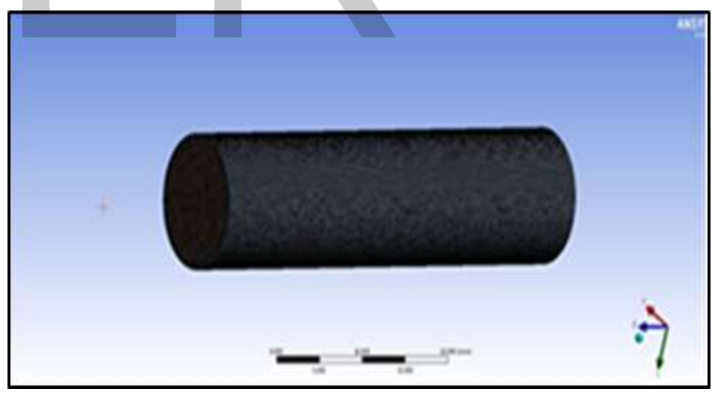


Fig. 2.4 Meshed geometry porosity 0.4

3 Analysis

The analysis part is carried by using ANSYS 14.5.Multiphase mixture model is used for the analysis. A property of two phase nitrogen at the saturation temperature is given as the input conditions. Pressure based numerical solver is selected and the flow is considered to be turbulent and unsteady. Viscous model used here is K-epsilon model. All the walls are considered as stationary. The problem is defined as an unsteady problem. Hybrid initialization is used for the initialization. Temperature of 300K is patched to both solid and fluid domain. The volume fraction of gaseous nitrogen is patched to 1 initially, assuming that the interior is initially filled with gaseous nitrogen. The analysis is done at a time step of 1 second.

The governing equations of the fluid flow are the mathematical statements of the laws of conservation of mass, momentum (Newton's Second law) and energy (First law of Thermodynamics). For the analysis of fluid flow, the fluid is regarded as a continuum.

4 Results and Discussions

The simulation of the flow of liquid nitrogen through the regenerator bed greatly facilitated the representation of temperature, pressure and phase distribution along the regenerator bed. The temperature at position 3 along regenerator was continuously noted with surface monitors and results were compared with experimental data.

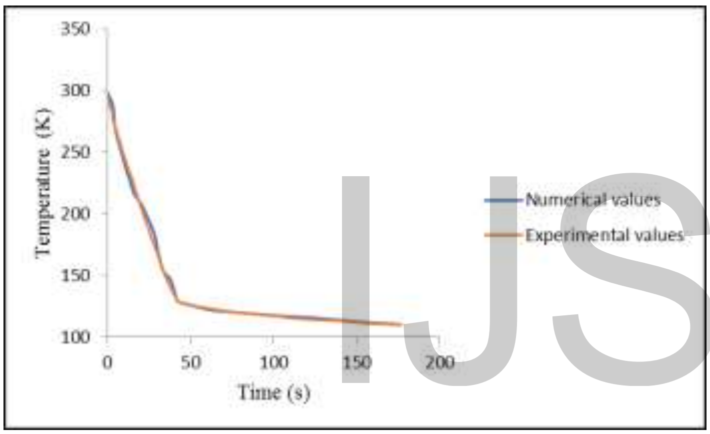


Fig. 4.1 Chill down comparison of experiment and simulation results for porosity 0.4

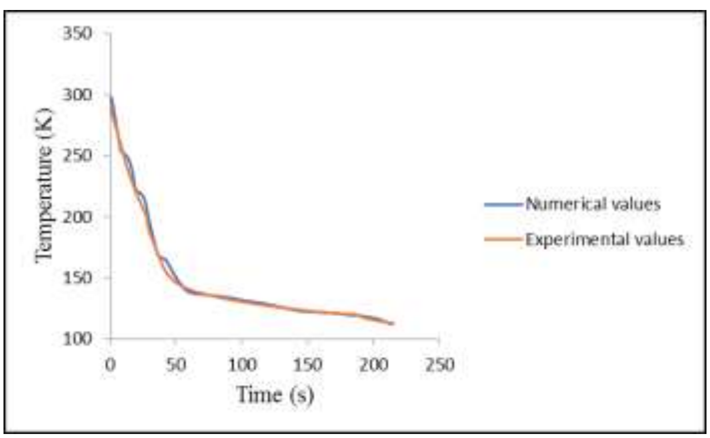
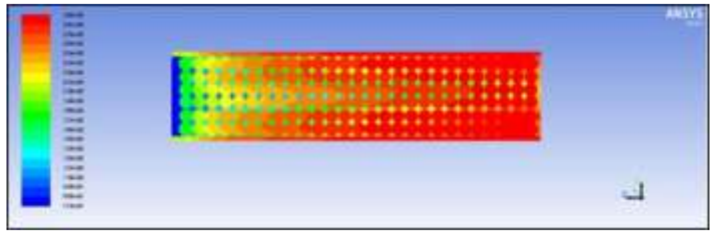


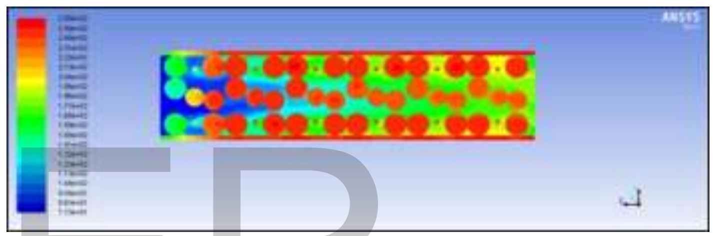
Fig. 4.2 Chill down comparison of experiment and simulation results for porosity 0.5

Figure 4.1 represents the chilldown along the regenerator with porosity 0.4. Here there is a rapid decrease in temperature till 41s and chilldown occurred at 178s. Also figure 4.2 represents the temperature time profile for porosity 0.5 where the rapid drop in temperature was observed till 53s and chilldown was obtained at 218s. For comparison with experiment results chilldown temperature was assumed to be at 110K.This may be due to the heat in leak to the regenerator. In the experiment nitrile rubber was used as insulator and the minimum temperature obtained was around 110K.

The temperature, pressure and phase contours from the CFD analysis are presented below.



(a). Contours of temperature for porosity 0.4



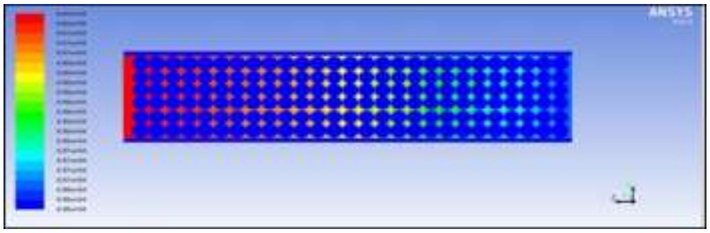
(b) Contours of temperature for porosity 0.5

Fig. 4.3 Sectional view of Regenerator (Temperature contour at 10s)

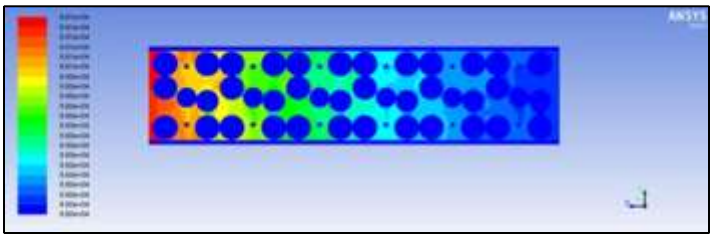
Figure 4.3 gives a representation of temperature distribution along the regenerator bed. It was noted that sphere packed bed with lower porosity values has low temperature gradient across the regenerator bed as noted in experiments. Temperature gradient exists within spheres along the regenerator bed. Chill down of sphere occur in stages. Materials have different specific heat capacities at different temperatures. The specific heat capacity and thermal conductivity decreases with drop in temperature. Packed spherical bed is the thermal mass for storage of heat energy. With increase in diameter, the ratio of thermal depth to diameter decreases. This is may be the reason for slower chilldown at higher porosities. This could contribute to the ineffectiveness of the regenerator.

As we mentioned earlier, though lowering of porosity values could enhance the heat transfer characteristics it earns penalties in the form of pressure drop. This is best expressed in the Fig. 4.4. Low porosity regenerator beds are showing a drastic pressure drop along the regenerator length.

The flow of working fluid along the regenerator bed is depicted in Fig.4.5. During initial conditions since the whole matrix is at ambient conditions, while the working fluid enters the regenerator bed it will absorb the latent heat and undergo phase change. This phenomenon of phase change has severe influence on the cold blow phase of the regenerator operation. The phase change of working fluid could deteriorate the thermal capacity of the working fluid. It will lead to ineffectiveness in extraction of heat energy from regenerator matrix.

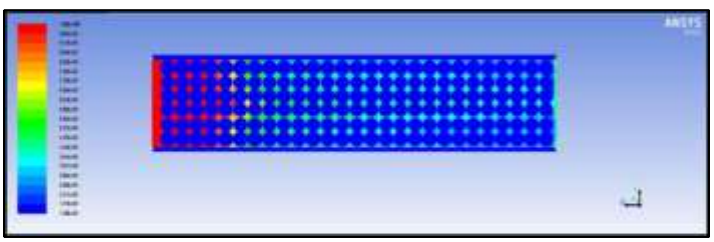


(a) Porosity 0.4

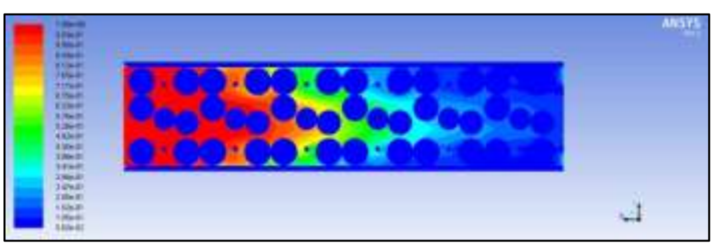


(b) Porosity 0.5

Fig. 4.4 Sectional view of Regenerator (Static pressure contour at 10s).



(a) Porosity 0.4



(b) Porosity 0.5

Fig. 4.5 Sectional view of Regenerator (Volume fraction of liquid at 10s)

5 Conclusion

Computational fluid dynamic analysis was conducted to investigate the temperature distribution and flow along a cryogenic regenerator. The CFD model is validated with experiment data. The effect of porosity on heat transfer phenomenon within the regenerator bed is clearly explained. The chill-down time is found decreasing with decrease in porosity and this is due to the fact that with the increase in diameter of the ball matrix, the ratio of thermal depth to diameter goes down. The low porosity regenerator exhibited greater temperature gradient along the regenerator.

Acknowledgment

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References

[1] Advances in Cryogenic Engineering, Vol. 12, Plenum Press, New York, 1967

[2] Ackermann, "R.A., Cryogenic Regenerative Heat Exchangers", Plenum Press, New York, 1997.

[3] Kay's W. M. and London A. L., "Compact Heat Exchangers", McGraw-Hill, 1998.

[4] Sodr, J.R. and Parise, J.A.R.,"Fluid flow pressure drop through an annular bed of spheres with wall effects", Experimental Thermal and Fluid Science Vol.17, pp 265-275. (1998)

[5] Barron R. F.," Cryogenic Heat Transfer, Taylor and Francis", 1999.

[6] Hao, X.H. and Ju, Y.L., "Experimental study on the low temperature regenerator packed with rectification meshes", Cryogenics Vol.50, pp 390–396. (2010)

[7] Pamuk, M.T. and Ozdemir, M., "Heat transfer in porous media of steel balls under oscillating flow", Experimental Thermal and Fluid Science Vol.42, 79–92. (2012)

[8] Pamuk, M.T. and Ozdemir, M., "Friction factor, permeability and inertial coefficient of oscillating flow through porous media of packed balls", Experimental Thermal and Fluid Science Vol.38, 134–139. (2012)

[9] Rout, S.K., Gupta, A.K., Choudhury, B.K., Sahoo, R.K. and Sarangi, S.K., "Influence of porosity on the performance of a Pulse Tube Refrigerator", A CFD study; Procedia Engineering Vol.51, pp 609 – 616. (2013)

[10] Trevizoli, P., Liu, Y., Tura, A., Rowe, A. and Barbosa J.Jr., "Experimental assessment of the thermal–hydraulic performance of packed-sphere oscillating-flow regenerators using water", Experimental Thermal and Fluid Science Vol.57, pp 324–334. (2014)

[11] Trevizoli, P.V., Peixer, G.F. and Barbosa J.Jr., "Thermal–hydraulic evaluation of oscillating-flow regenerators using water: Experimental analysis of packed beds of spheres", International Journal of Heat and Mass Transfer. (2016)

[12] Halkarni, S.S., Sridharan, A. and Prabhu, S.V., "Estimation of volumetric heat transfer coefficient in randomly packed beds of uniform sized spheres with water as working medium", International Journal of Thermal Sciences Vol.110, pp 340-355. (2016)

[13] El-Behery, S.M., Hussien, A.A., Kotb, H. and El-Shafie, M., "Performance evaluation of industrial glass furnace regenerator", Energy, pp 1-12. (2016)

[14] Trevizoli, P.V. and Barbosa J.Jr., "Thermal-hydraulic behavior and influence of carryover losses in oscillating-flow regenerators", Inter-

national Journal of Thermal Sciences Vol.113, pp 89-99. (2017)

[15] Abhiroop. V.M.,Vivek. R.I,Reby Roy. K.E., “Experimental investigations on chill down along packed spherical bed regenerator”. Proceedings of 26th National symposium on cryogenics and superconductivity,VECC Calcutta.(2017)

[16] K.E. Reby Roy, Jesna Mohammed, AbhiroopV.M., S. R. Thekkethil."Numerical investigations on the effect of slenderness ratio of matrix elements in cryogenic chill down process".26th International Cryogenic Engineering Conference, (7th-11th March 2016).IOP Conf. Series: Materials Science and Engineering 171 (March 2017)

[17] Abhiroop.V.M, R.I.Vivek ,K.E.Reby Roy, “Numerical investigations on the pressure drop characteristics along a compact regenerator”, Indian Journal of Cryogenics Vol.43,pp 114-118 (2018)