Numerical Simulations of Particle Deposition in Metal Foam Heat Exchangers

***E. Sauret[1], S. C. Saha[1], and Y. T. Gu[1]**

[1]School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, Brisbane, Australia.

*Corresponding author: Emilie.sauret@qut.edu.au

Key Words: *CFD Modeling, Metal Foam Heat Exchangers, Particle Tracking, Particle Deposition*

Abstract

Australia is a high-potential country for geothermal power with reserves currently estimated in the tens of millions of petajoules, enough to power the nation for at least 1000 years at current usage. However, these resources are mainly located in isolated arid regions where water is scarce. Therefore, wet cooling systems for geothermal plants in Australia are the least attractive solution and thus air-cooled heat exchangers are preferred. In order to increase the efficiency of such heat exchangers, metal foams have been used. One issue raised by this solution is the fouling caused by dust deposition. In this case, the heat transfer characteristics of the metal foam heat exchanger can dramatically deteriorate. Exploring the particle deposition property in the metal foam exchanger becomes crucial. This paper is a numerical investigation aimed to address this issue. Two dimensional (2D) numerical simulations of a standard one-row tube bundle wrapped with metal foam in cross-flow are performed and highlight preferential particle deposition areas.

Introduction

Increasing the electricity production while reducing the carbon emissions is a priority for many countries. Australia has a high-potential to produce geothermal power thanks to hot rocks reaching 300 degrees Celsius at approximately 5km under the surface (Hooman, 2010). However, these resources are mainly located in isolated arid areas. In such places, water is rare and precious and wet cooling systems for geothermal power plants are not the most appropriate solution. Instead, air-cooled heat exchangers appear a more suitable choice (Hooman & Gurgenci, 2010; Odabaee & Hooman, 2011).

For many thermal applications such as air conditioning or refrigeration, tube-bundles heat exchangers have been used and studied for many years (Kays & London, 1955). Their main advantages include: compactness, light weight and high efficiency. Fins were added to the tubes in order to improve the heat transfer thanks to a surface area increase. New developments led to further improve the efficiency of heat exchangers by replacing the fins by metal foams (Boomsma, Poulikakos, & Zwick, 2003). It has been recently suggested to replace finned tubes by metal foams in air-cooled heat exchangers for geothermal applications (Ejlali, Eljali, Hooman, & Gurgenci, 2009). Metal foams are fibrous materials which are becoming increasingly popular thanks to their attractive thermophysical properties such as high surface-to-volume ratio, low density, thermal and corrosion resistance and high mechanical strength and rigidity (Mahjoob & Vafai, 2008; T'Joen, De Jaeger, Huisseune, Van Herzeele, Vorst, & De Paepe, 2010). Heat transfer is enhanced by increasing the turbulence and mixing and dispersion induced by the ligaments of the foam as well as by high heat conductivity through the metallic ligaments. These properties lead to smaller, lighter and more efficient heat exchangers which become more attractive than conventional heat exchangers (Calmidi & Mahajan, 2000; Odabaee & Hooman, 2012; Obadaee, De Paepe, De Jaeger, T'Joen, & Hooman, 2013). Finally, the reduction in production cost also makes them more and more competitive.

For geothermal power plants, the use of binary cycle with a very low thermal efficiency requires high heat transfer rates. Hence, it is vital to make the technology highly efficient. To achieve this in

arid areas, air-cooled systems enhanced with metal foams are required. However, this technology still presents issues that need to be solved in order to achieve high efficiencies. Indeed, one issue raised by this enhancement technique is the fouling caused by the deposition of particles inside the pores of the metal foam. This deposition reduces the heat transfer rate between the flow and the metallic ligaments. The flow can be blocked causing an increase of pressure drop through the heat exchanger and reducing its permeability. All this affects negatively the efficient of the heat exchanger. As underlined by Obadaee et al. (Obadaee, De Paepe, De Jaeger, T'Joen, & Hooman, 2013), this issue has not been extensively studied in the current literature and needs further investigation especially numerical models capable of predicting the dust deposition and its effects on the heat exchanger performance.
Hooman et al. (Hooman, Tamayol, & Malayeri, 2012) investigated theoretically the impact of particle deposition in metal foam exchangers. Their findings outline the high pressure drop that can be reached due to blocked pores and the negative effect of particle deposition especially with high velocity flows. However, they assume a uniform layer distribution of dust on the foam surfaces, then noticing the importance of the challenges to model accurately such complex configurations.
Recently, Odabaee and Hooman (Odabaee & Hooman, 2012) performed simulations on a four-row tube bundle in cross-flow. The presented results showed that metal foam heat exchangers improve the heat transfer performance compared to conventional finned-tube heat exchangers at the expense of a slightly higher pressure drop. However, this study doesn't include any particles and the geometry of the metal foam is simply modelled as a porous media. In another study, Odabaee et al. (Obadaee, De Paepe, De Jaeger, T'Joen, & Hooman, 2013) numerically simulate the effects of particle deposition in a single-row metal foam-wrapped tube bundle. They compare cases with different fouling to clean metal foam and validate their simulations against some experiments (T'Joen, De Jaeger, Huisseune, Van Herzeele, Vorst, & De Paepe, 2010). However, the dust layer is assumed to be uniform with no particle modelling and the foam is considered as a simple porous media.
In order to extend the understanding of fouling in metal foam heat exchangers, this paper will look at the particle transport in a single-row tube bundle wrapped with metal foam and will give insights of the preferential particle deposition areas.

Approach

Geometry and Boundary Conditions

The geometry, as shown in Figure 1, is the same as the one presented in (T'Joen, De Jaeger, Huisseune, Van Herzeele, Vorst, & De Paepe, 2010) of a single-row tube bundle wrapped with an aluminium foam.
To reduce the cost of the simulations, a 2D case is chosen with symmetry conditions applied at the top and the bottom of the configuration. Symmetries are also applied at the front and back. The walls of the tubes have a fixed temperature of T_w=353K and we set a no slip condition. At the inlet, the flow temperature and velocity are set to respectively T_∞=298K and U_∞=3 m/s. At the outlet, the atmospheric pressure is specified.
The tube radius Rs is 0.006 m while the thickness of the foam is 0.004 m and the transversal tube pitch X_T is 0.028 m.

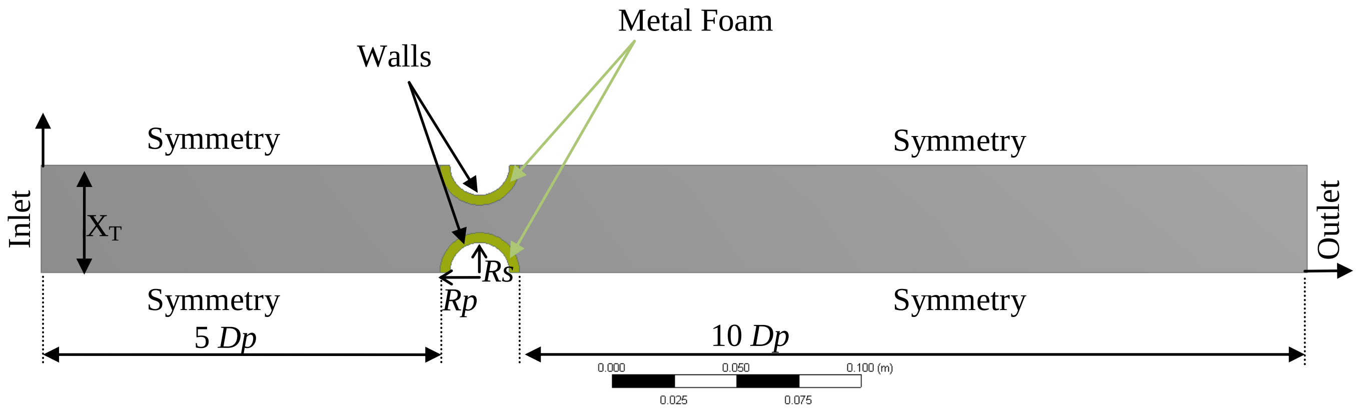

Figure 1: Single-row tube bundle wrapped with aluminum foam with boundary conditions

Mesh

An unstructured grid was obtained using ANSYS. The grid independency was performed and the selected mesh presented consisting of 86728 nodes is presented in Figure 2. An inflation layer was applied on the walls of the tubes with 5 layers and a growth rate of 1.3. At the interface between the foam and the main flow, the grid is refined with a growth rate of 1.3.

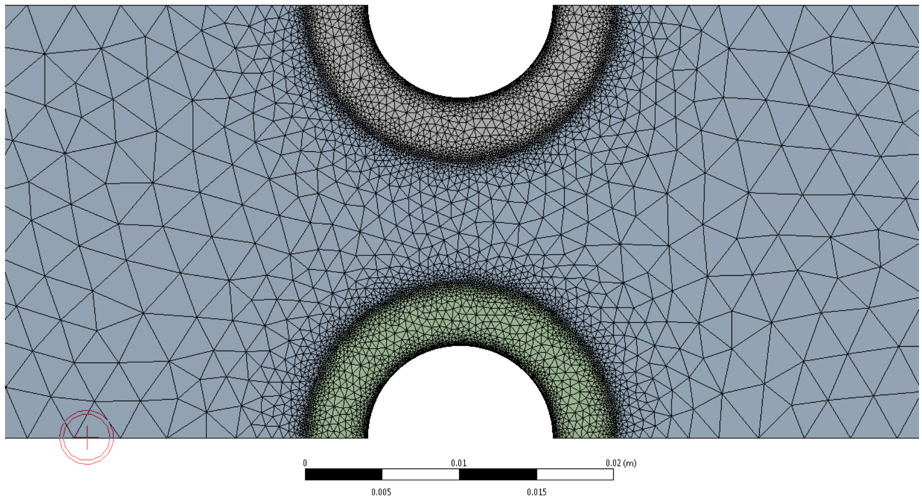

Figure 2: Mesh used for the present simulations

Numerical modeling

The particles injected at the inlet have the same velocity as the main flow through a zero slip velocity applied to them and a mass flow rate of 10^{-3} kg/s. We consider soot particles of density 2000 kg.m^{-3}. In our simulations, 5000 particles are introduced which was proved to be largely enough for a preliminary investigation. A normal distribution of particles was set with a minimum particle diameter of 10 µm, a maximum diameter of 250 µm, mean diameter of 50 µm and a standard deviation of 50 µm.
Our approach is to model the foam wrapped around the tubes as a porous media for which the experimental permeability and porosity are set as follows: K=5.3e-7 m^2 and ε=0.913. Because of the

complexity of the real foam geometry, the ligaments are not modeled inside the porous media. However, the aluminum properties of the ligaments are taken into account through an interfacial area density calculated from Calmidi and Mahajan (Calmidi & Mahajan, 2000) and an interfacial heat transfer coefficient from T'Joen, et al., 2010, respectively set to a_{sf}=1239.4m^{-1} and h_{sf}=200W.m^{-2}.K^{-1}. At the interface between the porous domain and the main flow, a conservative flux is applied.

ANSYS-CFX is used to perform the simulations. An Eulerian-Lagrangian approach was chosen for which the Eulerian models the continuous phase while the particle transport is modeled with a Lagrangian particle tracking model. In this study, the particulate phase is assumed to have negligible effects on the continuous phase thanks to a reduced volume fraction of particles entering the heat exchangers. As a consequence, a one-way coupling method is employed. This means that the continuous phase can influence the particles' trajectories but the particles have no impact on the flow pattern.

The standard k-ε model with scalable wall function is used to model the continuous phase.

We first assume a restitution coefficient at the wall to get the particles bouncing at the wall. We also run a case with a zero restitution coefficient. In that case, the particles reaching the wall stick to it and then disappear from the system.

Results and Discussion

First, the evolution of the pressure drop with the inlet velocity in Figure 3 was validated against the experiments from T'Joen et al. (T'Joen, De Jaeger, Huisseune, Van Herzeele, Vorst, & De Paepe, 2010).

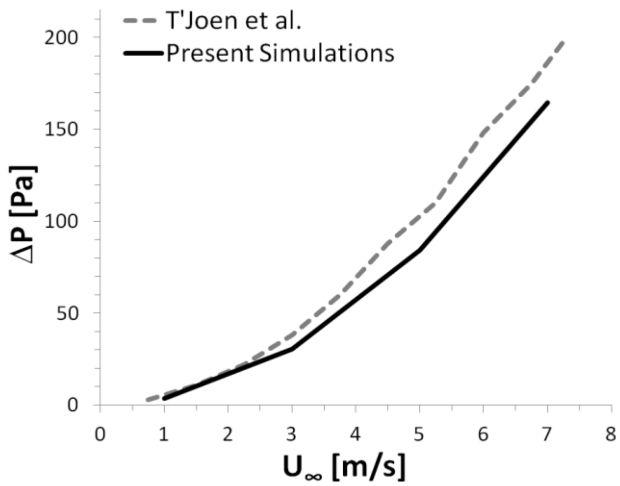

Figure 3: Comparison between the experiments (T'Joen, De Jaeger, Huisseune, Van Herzeele, Vorst, & De Paepe, 2010) and the present simulations of the evolution of the pressure drop with the inlet velocity.

The non-dimensional temperature distribution and the axial velocity are plotted in Figure 4. As this is a one-way coupling between the particles and the flow, the flow pattern is not affected by the particles and the particles mainly follow the same path as the flow. The high temperature areas near the tube wall correspond to the recirculation zone behind the cylinder. In this region, the backward velocity is really small (-0.6 m/s) compared to the main jet (around 10 m/s). As a consequence, the heat transfer is smaller at the rear of the tube than at the front. Indeed, the heat transfer coefficient at the wall behind the tube is around 3 W.m^{-2}.K^{-1} while it reaches 15 W.m^{-2}.K^{-1} at the front of the tube as shown in Figure 5.

As recently observed numerically by Nagendra et al.(Nagendra, Tafty, & Viswanathan, 2011), the regions of higher heat transfer correspond to the zones of preferential particle deposition. In our case, this is also observed in Figure 5 as when switching to the zero restitution coefficient, the particles deposition rate is mainly represented at the front of the tube (Figure 6) In addition, the case with a non-zero restitution coefficient also shows a larger volume fraction of particles at the front of the tube as shown in Figure 7. The transient simulation of this configuration was performed validating our conclusions (Figure 8).

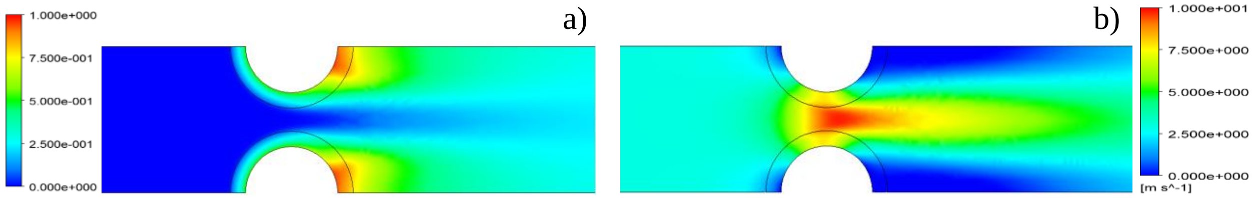

Figure 4: a) Non-dimensional temperature distribution and b) axial velocity distribution at U∞=3 m/s

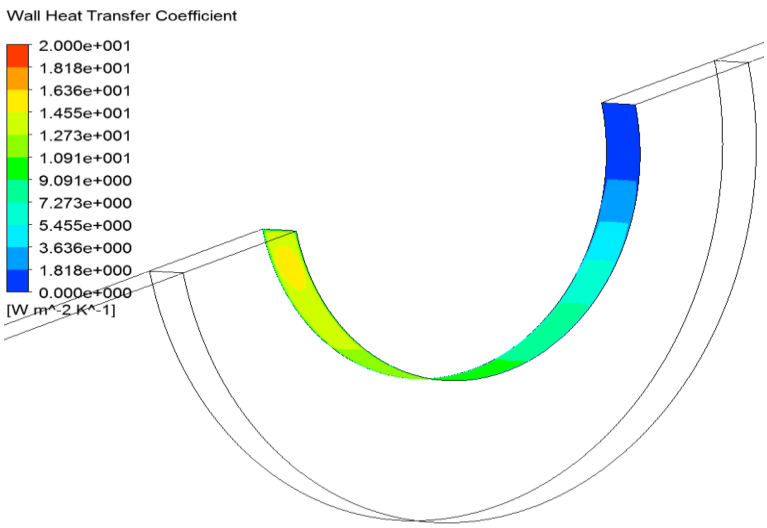

Figure 5: Wall Tube Heat Transfer Coefficient at U∞=3m/s

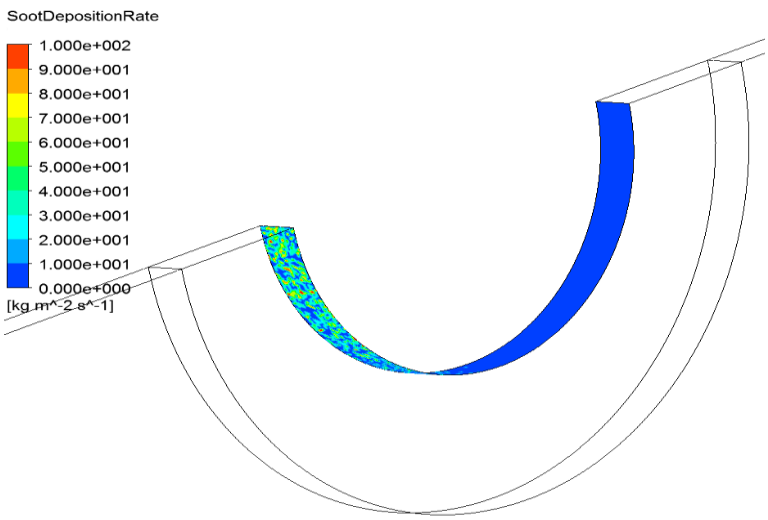

Figure 6: Wall mass flow density of particles at the tube wall in the case with a zero restitution coefficient at U∞=3 m/s

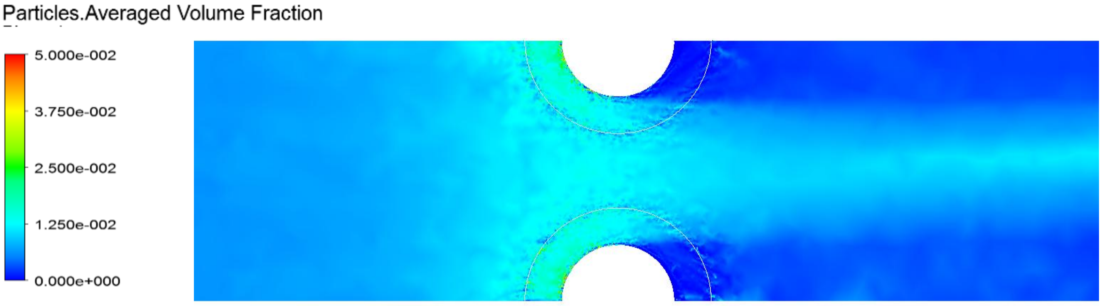

Figure 7: Averaged Volume Fraction of Particles for the steady simulation at U∞=3 m/s

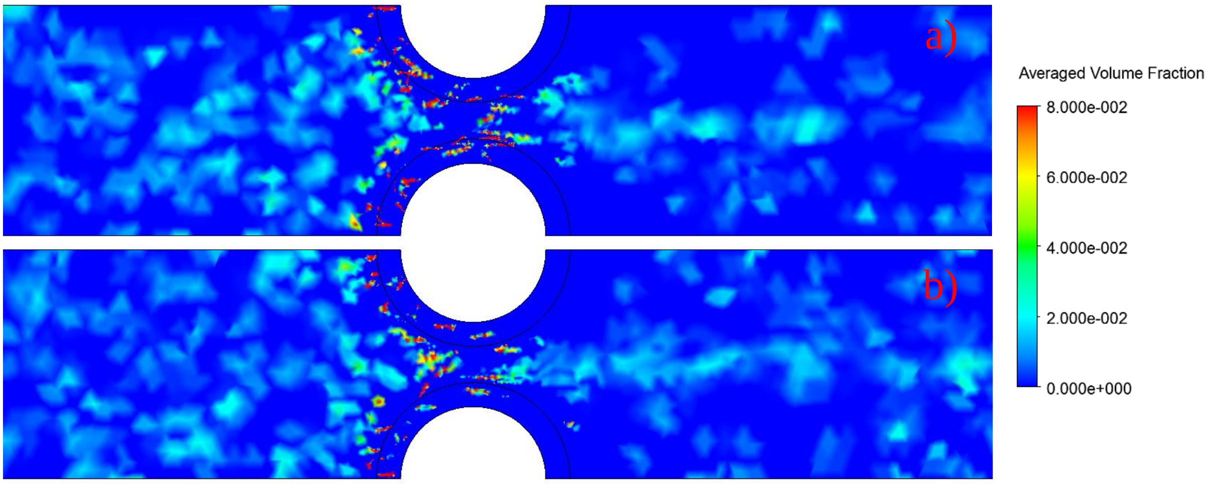

Figure 8: Averaged Volume Fraction of Particles for the transient simulation at U∞=3 m/s a) t=0.5s b) t=1s

Conclusions

This work is one of the first CFD studies carried out for the particle transport and deposition in metal foam heat exchangers. This preliminary study looked at the particle movements in a one-row tube bundle wrapped with metal foam and identified preferential deposition areas. It is shown that the front of the tubes is more exposed to particle deposition than the rear because of a higher velocity and a higher heat transfer in this region. The rear of the tube is subject to a large zone of recirculation which could lead to some particles moving back to the wall. However, due to the weak backward velocity and the low volume fraction of particles, this doesn't seem to happen.
Further investigations will be conducted including the effect of the wall temperature, the particle size distribution and other tube arrangements for which more experimental data will be available to extend the validation of our CFD.
Finally, new numerical models will be also developed in order to accurately model the particle deposition and re-entrainment process in metal foam heat exchangers.

Nomenclature

Rp, Dp	Tube+Foam radius and diameter, [m]
Rs	Tube Radius, [m]

X_T Transversal Tube Pitch, [m]
T Temperature, [K]
K Permeability, [m^2]
ε Porosity
a_{sf} Interfacial area density, [m^{-1}]
h_{sf} Interfacial heat transfer coefficient, [$W.m^{-2}.K^{-1}$]
t Time, [s]

Subscripts
w wall
∞ inlet

References

Boomsma, K., Poulikakos, D., & Ventikos, Y. (2003). Simulations of flow through open cell metal foams using an idealized periodic cell structure. *International Journal of Heat and Fluid Flow*, 34, pp. 825-834.

Boomsma, K., Poulikakos, D., & Zwick, F. (2003). Metal foams as compact high performance heat exchangers. *Mechanics of MAterials*, 35, pp. 1161-1176.

Calmidi, V. V., & Mahajan, R. L. (2000). Forced Convection in High Porosity Metal Foams. *Journal of Heat Transfer*, 122, pp.557-565.

Ejlali, A., Eljali, A., Hooman, K., & Gurgenci, H. (2009). Application of high porosity metal foams as air-cooled heat exchangers to high heat load removal systems. *International Communication in Heat and Mass Transfer*, 36, pp. 674-679.

Ghosh, I. (2009). How Good Is Open-Cell Metal Foam as Heat Transfer Surface? *Journal of Heat Trasnfer*, 131, pp. 1-8.

Hooman, K. (2010). Dry Cooling Towers as Condensers for Geothernmal Power Plants. *International Communication in Heat and MAss Transfer*, 37, pp. 1215-1220.

Hooman, K., & Gurgenci, H. (2010). Porous Medium Modeling of Air-Colled Condensers. *Transp. Porous Med.* , 84, pp. 257-273.

Hooman, K., Tamayol, A., & Malayeri, M. (2012). Impact of Particulate Deposition on the Thermohydraulic Performance of Metal Foam Heat Exchangers: A Simplified Theoretical Model. *Journal of Heat Transfer*, 134 (9), pp.1-7 .

Kays, W. M., & London, A. L. (1955). *Compact Heat Exchangers: A Summary of Basic Heat Transfer and Flow Friction Design Data.* Palo Alsot, California: National Press.

Mahjoob, S., & Vafai, K. (2008). A synthetis of fluid and thermal transport models for metal foam heat exchangers. *International Journal of Heat and Mass Transfer*, 51, pp. 3701-3711.

Nagendra, K., Tafty, D. K., & Viswanathan, A. K. (2011). Modeling of soot deposition in wavy-fin exhaust gas recirculator coolers. *International Journal of Heat and Mass transfer*, Vol. 54, pp. 1671-1681.

Odabaee, M., De Paepe, M., De Jaeger, P., T'Joen, C., & Hooman, K. (2013). Particle Deposition Effects on Heat Transfer from a Metal Foam-Wrapped Tube Bundle. *International Journal of Numerical Methods for Heat and Fluid Flows*, 23 (1), pp. 74-87.

Odabaee, M., & Hooman, K. (2011). Application of metal foams in air-cooled condensers for geothermal power plants: An optimization study. *International Communication in Heat and Mass Transfer*, 38, pp. 838-843.

Odabaee, M., & Hooman, K. (2012). Metal foam heat exchangers for heat transfer augmentation from a tube bank. *Applied Thermal Engineering*, 36, pp.456-463.

Odabaee, M., Hooman, K., & Gurgenci, H. (2011). Metal Foam Heat Exchangers for Heat Transfer Aigmentation from a Cylinder in Cross-Flow. *Transp. Porous Media*, 86, pp. 911-923.

T'Joen, C., De Jaeger, P., Huisseune, H., Van Herzeele, S., Vorst, N., & De Paepe, M. (2010). Thermo-hydraulic study of a single row heat exchanger consisting of metal foam covered round tubes. *International Journal of Heat and Mass Transfer, 53*, 3262-3274.