MINIMIZATION OF ENTROPY GENERATION AND PRESSURE DROP FOR HYBRID WIRE MESH REGENERATIVE HEAT EXCHANGER

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ABSTRACT
A single blow regenerator model is analysed to study the thermal performance of a metallic matrix based on the thermal losses and effectiveness of the regenerator. The losses due to irreversibility of the process can be calculated by the entropy generation concept. The entropy generation mainly depends on axial heat conduction, fluid friction and internal heat transfer. In this present study, the regenerator is designed and fabricated for the thermal performance analysis of uniform and hybrid mesh matrix arrangements. This paper gives how effectively a regenerator can be optimized based on the minimization of entropy generation and pressure drop. The hybrid mesh regenerator is made up of three zones of equal length with varying wire mesh sizes are analysed. From the results, the performance of hybrid mesh fixed bed regenerator provides better than uniform mesh fixed bed regenerator.

Keywords: regenerator, hybrid wire mesh, entropy generation.

1. INTRODUCTION
In a regenerator the hot and cold fluids pass alternately through a metallic matrix. Heat is stored in solid matrix comprising of dense packing materials with high specific heat and then it is recovered by blowing the cold fluid through the same bed. This implies that at a given time only one fluid flows through the heat exchanger. The regenerative heat exchanger has made them attractive to many applications such as gas turbine system, cryogenic industry and much more. In gas turbine system, regenerator is used to recover the heat from high temperature flue gas coming out of the gas turbine exhaust. It is extensively used in cryogenic industry, where compact and highly efficient heat exchangers are required.

Regenerators are primarily of two types - stationary (fixed) and rotary. The main advantage of fixed bed regenerators are less expensive, robust and can withstand extremely high or low temperature operating conditions. Regenerator is stacked with wire matrix, higher solid particles implies large surface area exposed to heat transfer thereby increasing thermal performance with more pressure drop in the regenerator. The losses in the regenerators and heat exchangers are calculated from the entropy productions.

There are two situations, heat conduction domination and flow resistance domination. The losses in the regenerator and heat exchanger are compared from the entropy productions due to the various irreversible processes [1]. In regenerator inner tube the oversize wire screen is used to reduce the flow leakage. Curve matching and maximum slope methods are used to predict the NTU values [2]. The approximate solution is derived to calculate the temperature profiles and regenerator effectiveness in a two phase model for the gas and storage matrix [3]. Ergun equation is used to predict the pressure loss in packed bed filters [4]. The modified Ergun equation is used to analyze the flow through porous media with inertia effects and micromechanical based study of moderate Reynolds number by using a CFD approach [5]. Regenerator optimization is based on the calculation of entropy production rates from the processes of axial thermal conduction, flow resistance and internal heat resistance was analysed for low temperature flow condition [6].

This paper deals with high temperature flow condition. A theoretical model is developed to predict the effective thermal conductivity and volumetric porosity in copper wire screens [7]. A new methodology is developed to calculate the specific surface area and thermal conductivity of wire screen matrix [8]. Nusselt number and friction pressure drop correlation equations were numerically derived for woven wire matrix regenerator [9, 10]. A numerical model for the calculation of regenerator is developed by using control volume concept [11]. The Entropy Generation Minimization (EGM) based simple models are used to find the optimal results in real (irreversible) devices and processes with constraints as finite size and finite time [12].

In the present work, the regenerator can be designed in such a way that for the optimal performance according to the Entropy Generation Minimization (EGM) method and the optimized regenerator is experimentally analysed. The performance of regenerator mainly depends on thermal losses and effectiveness of the regenerator. To improve the performance of regenerator need large heat transfer area and ultimately large pressure drop is unavoidable.

The main objective of this paper is to maximize the effectiveness of the regenerator, and to minimize the pressure drop. This can be achieved by optimizing the wire mesh sizes within the regenerator volume, instead of using a uniform wire mesh size. In this regenerator length is stacked with combination of three wire mesh size each section carries different mesh size. The optimized regenerator is then analyzed.
2. REGENERATOR OPTIMIZATION

The optimization of regenerator is done by selecting the most appropriate design parameters, such as matrix geometry, matrix material, matrix arrangements and number of heat transfer units. The entropy generation due to irreversibility of the process has to be analysed but due to the practical difficulties, it cannot be done on existing regenerator. Hence a single blow model has been generated and analysed.

3. LOSSES

In this section, we will discuss the entropy production for four relevant processes. The loss occurring in the wire mesh filled regenerator can be expressed in terms of entropy production.

3.1. Axial heat conduction in the gas

The entropy generation rate per unit length due to axial heat conduction in the gas can be written as [6]

\[
\frac{dS_{cg}}{dl} = A_g \frac{Nu}{T^2} \left( \frac{dT}{dl} \right)^2
\]

\[ (1) \]

\[ A_g = (1 - f)A_r \]  \[ (2) \]

\[ Nu = \frac{h_A k_g}{k_g} \]  \[ (3) \]

With \( A_g \) is the free flow fluid passage area of the regenerator where \( A_r \) is the area of cross section and \( f \) is the filling factor, \( k_g \) is the thermal conductivity of the gas, \( Nu \) is the Nusselt number for the regenerator, \( T \) is the gas temperature and \( l \) is the coordinate length.

3.2. Axial heat conduction through matrix material

The entropy generation rate per unit length due to axial heat conduction through the material can be written as [6]

\[
\frac{dS_{cm}}{dl} = A_g \frac{k_s}{T^2} \left( \frac{dT}{dl} \right)^2
\]

\[ (4) \]

With \( A_g = f A_r, k_s \) is the thermal conductivity of the solid material.

3.3. Fluid friction

The entropy generation per unit length due to gas flow friction (viscous resistance) can be written as [6]

\[
\frac{dS_{fr}}{dl} = \frac{2 \mu (n V_m)^2}{A_r T^2}
\]

\[ (5) \]

With \( z_{fr} = \frac{32}{d_i^2} \)

\[ (6) \]

with \( \mu \) is the viscosity of the gas, \( V_m \) is the molar volume of the fluid, \( n \) the molar flow of the fluid, \( A_r \) the cross section of the regenerator, \( z_{fr} \) is the geometrical factor.

3.4 Internal heat transfer

The entropy generation per unit length due to internal heat transfer between gas and material can be written as [6]

\[
\frac{dS_{ht}}{dl} = z_{ht} \frac{c_p n^2}{A_r T^2 k_g} \left( \frac{dT}{dl} \right)^2
\]

\[ (7) \]

With

\[ z_{ht} = \frac{d^2_h}{12 l} \]

\[ (8) \]

\[ d_h = d_w \frac{(1-f)}{f} \]

\[ (9) \]

with \( c_p \) is the molar specific heat capacity of the gas, \( z_{ht} \) is the geometrical factor, \( d_h \) is the hydraulic diameter for the perfectly stacked screen. The heat transfer coefficient “h” which can be estimated through relation given by Ackerman [13]

\[ Nu = 0.68 Re^{0.6} Pr^{0.33} \]

\[ (10) \]

The total entropy generation is the sum of entropy generation due to axial heat conduction in gas and

**Nomenclature**

- \( A \) cross-sectional area \((m^2)\)
- \( c_p \) gas molar heat capacity \((J/mol \ K)\)
- \( d_i \) housing inner diameter \((m)\)
- \( f \) filling factor
- \( f_r \) friction factor
- \( L \) regenerator length
- \( l \) characteristic length \((m)\)
- \( m \) mass flow rate \((kg/s)\)
- \( n \) molar flow \((mol/s)\)
- \( Nu \) Nusselt number
- \( p \) pressure \((pa)\)
- \( Q \) flow rate \((m^3/s)\)

**Greeks**

- \( \rho \) density \((kg/ m^3)\)
- \( k \) thermal conductivity of the gas \((W/mK)\)

**Subscripts**

- \( cg \) axial heat conduction in the gas
- \( cm \) axial heat conduction in the material
- \( g \) gas
- \( r \) regenerator
- \( w \) wire mesh
solid matrix, viscous friction and heat transfer between gas and solid matrix [6].

\[
S_{\text{total}} = \left(1 - \frac{1}{2}\right) \frac{\text{Nu}}{D_s} \left(\frac{d\mu}{d\mu'}\right) + \frac{k_2}{T_i} \left(\frac{dT}{d\mu'}\right) + \frac{z m (\delta L_m)^2}{\Delta T_i g} + \frac{\mu Z (\delta V)^2}{A T_i} \sum \frac{A}{L_i} \frac{T_i}{T'} \left(\frac{dT}{d\mu'}\right) \sum \frac{L_i}{A} \frac{T_i}{T'} \left(\frac{dT}{d\mu'}\right)
\]

(11)

3.5 Pressure loss

In fluid flow through porous media the pressure loss can be determined by using Ergun equation as [5],

\[
\Delta P = 150 \left(1 - \frac{1}{2}\right) \frac{\rho}{\mu^2} \frac{V}{D_p} + 1.75 \left(1 - \frac{1}{2}\right) \frac{V}{\mu} \frac{\rho}{D_p}
\]

(12)

Table-1. Performance of uniform mesh regenerator for high temperature.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Porosity</th>
<th>Wire diameter (m)</th>
<th>Number of screens</th>
<th>Axial heat conduction (W/mK)</th>
<th>Flow resistance (W/mK)</th>
<th>Internal heat transfer (W/mK)</th>
<th>Total entropy generation (W/mK)</th>
<th>Pressure drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.804</td>
<td>6.35E-04</td>
<td>787</td>
<td>0.00183</td>
<td>18.72</td>
<td>9756</td>
<td>9.775E+03</td>
<td>174</td>
</tr>
<tr>
<td>12</td>
<td>0.783</td>
<td>5.84E-04</td>
<td>856</td>
<td>0.00161</td>
<td>28.61</td>
<td>6446</td>
<td>6.475E+03</td>
<td>275</td>
</tr>
<tr>
<td>14</td>
<td>0.78</td>
<td>5.08E-04</td>
<td>984</td>
<td>0.00145</td>
<td>39.16</td>
<td>5092</td>
<td>5.131E+03</td>
<td>336</td>
</tr>
<tr>
<td>16</td>
<td>0.774</td>
<td>4.57E-04</td>
<td>1094</td>
<td>0.00133</td>
<td>51.86</td>
<td>4053</td>
<td>4.105E+03</td>
<td>376</td>
</tr>
<tr>
<td>18</td>
<td>0.759</td>
<td>4.32E-04</td>
<td>1157</td>
<td>0.00121</td>
<td>68.64</td>
<td>3088</td>
<td>3.157E+03</td>
<td>416</td>
</tr>
<tr>
<td>20</td>
<td>0.805</td>
<td>3.15E-04</td>
<td>1587</td>
<td>0.00121</td>
<td>75.13</td>
<td>3711</td>
<td>3.786E+03</td>
<td>457</td>
</tr>
<tr>
<td>22</td>
<td>0.785</td>
<td>3.15E-04</td>
<td>1587</td>
<td>0.00111</td>
<td>96.05</td>
<td>2791</td>
<td>2.887E+03</td>
<td>512</td>
</tr>
<tr>
<td>24</td>
<td>0.766</td>
<td>3.15E-04</td>
<td>1587</td>
<td>0.00103</td>
<td>119.49</td>
<td>2169</td>
<td>2.288E+03</td>
<td>714</td>
</tr>
<tr>
<td>26</td>
<td>0.762</td>
<td>2.95E-04</td>
<td>1694</td>
<td>0.00097</td>
<td>142.42</td>
<td>1880</td>
<td>2.022E+03</td>
<td>822</td>
</tr>
<tr>
<td>28</td>
<td>0.744</td>
<td>2.95E-04</td>
<td>1694</td>
<td>0.00092</td>
<td>172.84</td>
<td>1358</td>
<td>1.531E+03</td>
<td>1116</td>
</tr>
</tbody>
</table>

With \( \varepsilon \) is the fractional void volume, \( g \) is the dimensional constant (kg,m/Ns²) and \( D_p \) is the effective diameter of particles.

4. RESULTS AND DISCUSSIONS

In the current investigation, steel wire screen and air were selected as matrix and fluid, respectively. The regenerator analysis of a fixed bed wire mesh matrix has been carried for a typical flow condition to study the performance between uniform and hybrid mesh matrix arrangement based on the entropy generation. The entropy generation analysis is carried out for high temperature flow conditions.

Table-2. Physical properties and geometric data used in the analytical solution of this system.

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_i )</td>
<td>0.053 m</td>
</tr>
<tr>
<td>( L_{in} )</td>
<td>0.200 m</td>
</tr>
<tr>
<td>( L_{out} )</td>
<td>0.045 m</td>
</tr>
<tr>
<td>( \dot{m} )</td>
<td>6.929 x 10⁻³ Kg/s</td>
</tr>
<tr>
<td>( c_p )</td>
<td>1000 J/kg⁻¹ K⁻¹</td>
</tr>
</tbody>
</table>
4.2. Hybrid mesh regenerator

In hybrid mesh regenerator, 16 mesh combinations are analysed and the results are presented in Table-3. Figures 3 & 4 shows the hybrid mesh combination 10-16-20 is optimum for entropy production rate due to internal heat transfer with optimum pressure drop. Efficient regenerator should have a higher heat transfer rate and minimum pressure drop. But to meet these two requirements at a time is impossible. In order to compromises both the requirements optimized regenerator

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Axial heat conduction (W/mK)</th>
<th>Flow resistance (W/mK)</th>
<th>Internal heat transfer (W/mK)</th>
<th>Total entropy generation (W/mK)</th>
<th>Pressure drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-12-14</td>
<td>0.00166</td>
<td>32.22</td>
<td>7850</td>
<td>7.882E+03</td>
<td>270</td>
</tr>
<tr>
<td>10-12-16</td>
<td>0.00161</td>
<td>36.96</td>
<td>7602</td>
<td>7.639E+03</td>
<td>302</td>
</tr>
<tr>
<td>10-12-18</td>
<td>0.00158</td>
<td>43.21</td>
<td>7371</td>
<td>7.414E+03</td>
<td>362</td>
</tr>
<tr>
<td>10-12-20</td>
<td>0.00158</td>
<td>45.63</td>
<td>7520</td>
<td>7.566E+03</td>
<td>279</td>
</tr>
<tr>
<td>10-14-16</td>
<td>0.00154</td>
<td>41.07</td>
<td>7140</td>
<td>7.181E+03</td>
<td>322</td>
</tr>
<tr>
<td>10-14-18</td>
<td>0.00151</td>
<td>47.32</td>
<td>6910</td>
<td>6.957E+03</td>
<td>382</td>
</tr>
<tr>
<td>10-14-20</td>
<td>0.00151</td>
<td>49.74</td>
<td>7058</td>
<td>7.108E+03</td>
<td>299</td>
</tr>
<tr>
<td>10-16-18</td>
<td>0.00147</td>
<td>52.27</td>
<td>6555</td>
<td>6.607E+03</td>
<td>378</td>
</tr>
<tr>
<td>10-16-20</td>
<td>0.00147</td>
<td>54.69</td>
<td>6504</td>
<td>6.759E+03</td>
<td>325</td>
</tr>
<tr>
<td>10-18-20</td>
<td>0.00143</td>
<td>56.22</td>
<td>6075</td>
<td>6.436E+03</td>
<td>376</td>
</tr>
<tr>
<td>12-14-16</td>
<td>0.00140</td>
<td>56.15</td>
<td>5822</td>
<td>5.868E+03</td>
<td>350</td>
</tr>
<tr>
<td>12-14-18</td>
<td>0.00137</td>
<td>58.40</td>
<td>5591</td>
<td>5.643E+03</td>
<td>410</td>
</tr>
<tr>
<td>12-14-20</td>
<td>0.00137</td>
<td>58.82</td>
<td>5740</td>
<td>5.795E+03</td>
<td>357</td>
</tr>
<tr>
<td>14-16-18</td>
<td>0.00127</td>
<td>61.61</td>
<td>4582</td>
<td>4.644E+03</td>
<td>454</td>
</tr>
<tr>
<td>14-16-20</td>
<td>0.00127</td>
<td>64.03</td>
<td>4731</td>
<td>4.795E+03</td>
<td>371</td>
</tr>
<tr>
<td>16-18-20</td>
<td>0.00119</td>
<td>75.70</td>
<td>3899</td>
<td>3.975E+03</td>
<td>444</td>
</tr>
</tbody>
</table>
gives solution for this. Based on the results obtained optimized hybrid mesh provides better thermal performance than uniform mesh regenerator.

![Figure-3](image-url)  
**Figure-3.** Entropy production rates due to internal heat transfer and flow resistance for uniform mesh

![Figure-4](image-url)  
**Figure-4.** Entropy production rates due to internal heat transfer and pressure drop for hybrid mesh.

4.3. Experimental validation

In this experimental analysis, a single blow model is used where only one blow of the fluid is considered, the hot or cold fluid passed through the matrix for the particular time period. After the flow period, the temperature of fluid leaving the regenerator is monitored. The efficiency of the regenerator can be calculated from the fluid outlet temperature.

The single blow test apparatus is shown in Figure-5. It consists of a test section containing the test matrix, air switch to allow warm or cold air to pass through the matrix, a heater to control the temperature of the air entering the matrix and a flow meter for measuring the flow rate of fluid through the matrix. This system mainly consists of test section packed with stainless steel wire mesh matrix which is connected to the electric air heater through control valve The function of control valve is to control the mass flow rate of hot air.

![Figure-5](image-url)  
**Figure-5.** Experimental setup.

<table>
<thead>
<tr>
<th>Mesh type</th>
<th>Mesh number</th>
<th>Matrix length (m)</th>
<th>No. of screens</th>
<th>Pressure drop (pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Analytical results</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Atmospheric air</td>
</tr>
<tr>
<td>Uniform Mesh</td>
<td>12 Mesh</td>
<td>0.02</td>
<td>17</td>
<td>99.59</td>
</tr>
<tr>
<td></td>
<td>16 Mesh</td>
<td>0.02</td>
<td>22</td>
<td>150.40</td>
</tr>
<tr>
<td>Hybrid Mesh</td>
<td>12 – 16 Meshes</td>
<td>0.02</td>
<td>19</td>
<td>124.99</td>
</tr>
</tbody>
</table>

![Table-4](image-url)  
**Table-4.** Comparison of analytical and experimental pressure drop for uniform and hybrid mesh regenerator.
The blower of capacity 25 CFM is coupled with electric air heater. It is designed to heat up the air up to 200°C. During heating process air flow direction will be from blower to regenerator test section through the electric air heating chamber. During regenerating process air is made to pass in opposite direction which is blower to matrix. This is done to retrieve heat from the matrix to the air.

Experimental analysis has been carried out for the uniform and hybrid mesh regenerators for the typical flow condition. In this analysis the wire mesh 12 and 16 were tested for both uniform and Hybrid mesh regenerators. The hybrid mesh regenerator made up with two zones of equal length. The effectiveness of the two different uniform and hybrid mesh regenerators have been investigated experimentally. This results which inferred are plotted in Figure-6 & Figure-7 and understand that the hybrid mesh regenerator gives higher effectiveness instead of using uniform mesh regenerator.

As stated earlier, a regenerator requires higher heat transfer rate and minimum pressure drop for its maximum efficiency, but practically it is not possible. For comparison, analytical and experimental pressure drop for uniform and hybrid mesh regenerators packed with 12 and 16 mesh wire screens are presented in Table – 4 and understands that the hybrid mesh regenerator gives the optimal pressure drop.

CONCLUSIONS

In the current investigation, the thermal performance and pressure drop for uniform and hybrid mesh regenerators were critically reviewed and compared. The performance of the regenerator is improved by optimizing the design from uniform mesh regenerator to a Hybrid regenerator under specific operating conditions are obtained. The optimized regenerator is verified with the entropy generation minimization concept.

The validation results show that, in uniform mesh regenerator there is a continuous decrement in entropy generation and gradual raise in pressure drop, when the mesh size increases. But regenerator requires minimum entropy generation and pressure drop. Based on the results obtained the hybrid mesh regenerator, mesh combination of 10-16-20 provides optimized heat transfer rate and pressure drop than the uniform mesh regenerator.

REFERENCES


