VIBRATION EFFECTS ON NATURAL CONVECTION IN A POROUS LAYER HEATED FROM BELOW WITH APPLICATION TO SOLIDIFICATION OF BINARY ALLOYS

by
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Outline

- Purpose of study
- Experimental method and results
- Theoretical method of solution
- Theoretical results and discussion
- Conclusions
- Recommendations
- Acknowledgments
Purpose of study

Identifying regimes of enhancement in heat transfer is one of the aims and therefore the purpose of this study is to investigate the effect of heat transfer alone on a porous layer (representing the mushy layer in the solidification process) subject to vibration and particularly identifying thermal resonance occurrence and whether the thermal resonance may or may not enhance the heat transfer. A sufficiently wide parameter regime is to be considered, yet the work is to be undertaken via analytical or combined analytical-numerical methods in order to be able to draw qualitative as well as quantitative conclusions.
Figure 1: Picture and schematic of experimental set-up showing the thermal bath, vibration exciter, test sample location, and cantilever system attached to the rigid frame.
Table 1: Samples showing the relationship between the enhancement ratio $Gr_v/Gr$ and the average density of solidified paraffin wax. Every sample is the average of five samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Frequency (Hz)</th>
<th>$R_v = \frac{Gr_v}{Gr}$</th>
<th>Average Density [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>865.73</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.51</td>
<td>862.45</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>3.2</td>
<td>849.55</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>51</td>
<td>858.19</td>
</tr>
<tr>
<td>5</td>
<td>110</td>
<td>62</td>
<td>859.44</td>
</tr>
<tr>
<td>6</td>
<td>130</td>
<td>86.6</td>
<td>857.64</td>
</tr>
<tr>
<td>7</td>
<td>300</td>
<td>461</td>
<td>866.53</td>
</tr>
</tbody>
</table>

Table 2: Measured mass of solidified paraffin wax at different times under no vibration for five samples.

<table>
<thead>
<tr>
<th>Time (minutes)</th>
<th>Sample 1 Mass [g]</th>
<th>Sample 2 Mass [g]</th>
<th>Sample 3 Mass [g]</th>
<th>Sample 4 Mass [g]</th>
<th>Sample 5 Mass [g]</th>
<th>Average Mass [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>15.45</td>
<td>15.65</td>
<td>15.61</td>
<td>15.52</td>
<td>15.67</td>
<td>15.58</td>
</tr>
<tr>
<td>10</td>
<td>17.75</td>
<td>17.77</td>
<td>17.98</td>
<td>17.68</td>
<td>17.97</td>
<td>17.83</td>
</tr>
<tr>
<td>20</td>
<td>19.88</td>
<td>19.84</td>
<td>19.90</td>
<td>19.68</td>
<td>19.70</td>
<td>19.80</td>
</tr>
</tbody>
</table>
Table 3: Measured mass of solidified paraffin wax at different times under a vibration frequency of 100 Hz for five samples.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>18.15</td>
<td>18.18</td>
<td>18.16</td>
<td>18.27</td>
<td>18.34</td>
<td>18.22</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>19.10</td>
<td>19.01</td>
<td>19.05</td>
<td>18.95</td>
<td>18.99</td>
<td>19.02</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20.24</td>
<td>20.29</td>
<td>20.11</td>
<td>20.14</td>
<td>20.27</td>
<td>20.21</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>21.06</td>
<td>21.09</td>
<td>20.86</td>
<td>21.05</td>
<td>20.94</td>
<td>21.00</td>
<td></td>
</tr>
<tr>
<td><strong>Initial mass [g]</strong></td>
<td><strong>21.06</strong></td>
<td><strong>21.09</strong></td>
<td><strong>20.86</strong></td>
<td><strong>21.05</strong></td>
<td><strong>20.94</strong></td>
<td><strong>21.00</strong></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2: Mass of solid paraffin wax formed versus time for no vibration and vibration frequency of 100 Hz for five samples of each.
Figure 3: Average mass of solid paraffin wax formed versus time for no vibration and vibration frequency of 100 Hz.
5 minutes

20 minutes

Final solidification time
VIBRATION EFFECTS ON HEAT TRANSFER DURING SOLIDIFICATION OF PARAFFIN

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ABSTRACT

Previous work looked at the solidification process of PCM (phase change material) paraffin wax. Experimental results were compared with numerical work done in CFD package FLUENT. In the current study, the effects of vibration on heat transfer during the solidification process of PCM in a sphere shell are investigated. Enhancement of heat transfer results in quicker solidification times and desirable mechanical properties of the solid. The amount of PCM used was kept constant during each experiment by using a digital scale to check the weight, and thermocouple to check consistent temperature. A small amount of air was present in the sphere so that the sphere was not filled completely. Commercially available paraffin wax, RT35, was used in the experiments. Experimentations were done on a sphere of 40 mm diameter, wall temperature 20°C below mean solidification temperature, and consistent initial temperature. A vibration frequency was varied from 10-300 Hz was applied to the set-up and results compared with that of no vibration. Samples were taken at different times during the solidification process and compared with respect to solid material present.

INTRODUCTION

Directional solidification is a topic of wide interest due to its importance to the iron and steel industry. Solute convection in the solidification process results in channel formation, which has a freckle like appearance in the cross-section and has a critical effect on the mechanical strength of casting. Rotational effects [1,2,3] as well as gravitational effects [4,5] on solidification are well documented and show a stabilizing effect on convection for the synchronous solutions, but slowly destabilizes convection for the region of sub-harmonic solutions [6]. Additional numerical results for convection in a porous layer subjected to vibration and heated from below, show that increasing the frequency of vibration causes the amplitude of convection to approach zero [7].

Experimental results using a hand tapping technique have shown an improvement in density, hardness, ultimate tensile strength, and % elongation [8]. This has proven to be an inexpensive technique for improving the properties of long freezing range LM25 or 356 Al alloys.

Even though the hand tapping technique proves useful, it is unpractical for mass production. This method is also susceptible on an uneven vibration amplitude and frequency due to the human factor. Further experimentation is required to prove the necessity for implementing the vibration technique, and a better method is required to introduce vibrations.

PROBLEM FORMULATION

Numerical:

Figure 1: Porous media heated from below, subject to vibration.

Figure 4: A two-dimensional rectangular domain heated from below (or cooled from above) subject to accelerations due to gravity and imposed vibrations.
Governing Equations:

\[
\left[ \frac{1}{Pr_D} \frac{\partial}{\partial \tilde{t}} + 1 \right] \nabla^2 \psi + Ra \left[ 1 + \delta \sin(\tilde{\omega} \tilde{t}) \right] \frac{\partial T}{\partial x} = 0
\]

\[
\psi_v = A_{11} \sin \left( \frac{\pi x}{L} \right) \sin(\pi z)
\]

\[
\frac{\partial T}{\partial t} + \frac{\partial \psi}{\partial z} \frac{\partial T}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial T}{\partial z} = \nabla^2 T
\]

\[
T_v = B_{11} \cos \left( \frac{\pi x}{L} \right) \sin(\pi z) + B_{02} \sin(2\pi z)
\]

\[
\dot{X} = -\alpha (X - Y) + \alpha \delta Y \sin(W)
\]

\[
\dot{Y} = -Y + RX - (R - 1) X Z
\]

\[
\dot{Z} = 4\gamma (XY - Z)
\]
Theoretical results and discussion
Conclusions

- All anticipated regimes of natural convection were indeed obtained, including periodic, quasi-periodic, and chaotic (weak-turbulent) regimes.

- The anticipated nonlinear thermal resonances do not affect substantially the average heat transfer by convection because the solutions seem to behave quite symmetrically around the average values and therefore the averaging process removes any such instantaneous large amplitude effects.

- The combined heat and mass transfer by convection is therefore the remaining reason for the improvement observed experimentally in the solidification process subject to vibrations.

- With hindsight one may be able to anticipate that one of the mass transfer mechanisms, namely the freckles formation, and the consequent variation of solid fraction (or equivalently the porosity) is the probable cause for the improvement in the solidification process when subjected to vibrations. This mechanism is expected to depend strongly on convection heat transfer as well as convection mass transfer in the porous medium (mushy layer).
Recommendations

Based on the conclusions a clear course of action can be recommended in terms of follow-up studies having the objective of fully understanding the causes behind the experimentally established improvement of the properties of the cast in the solidification process. It seems that a combination of heat and mass transfer processes might provide the explanation for such improvement. Therefore a substantial further development of the model developed in the present study to include mass transfer is recommended as the next step. While models of heat and mass transfer within a mushy layer were derived previously and were presented in the literature survey, they have the limitation of being applied for a very narrow range of thermal and solute Rayleigh numbers, i.e. very close to the critical values of these Rayleigh numbers, making the results and conclusions quite limited. On the other hand, other attempts focused on full numerical simulation which suffers from a too large parameter space, i.e. too large number of parameters and consequently a voluminous number of results and graphs that are difficult to analyse. Extending the model proposed in the present study to include mass transfer and particularly to model the variation of the porosity (or its equivalent solid fraction) in time as well as in space and consequently the freckles formation is a very challenging and possibly extremely time consuming task, but nevertheless it is needed as the next step recommended based on the present study conclusions.
Acknowledgments

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Thank you

Questions???