SOLUTION OF THE TEMPERATURE PROBLEM FOR A HORIZONTAL TUNNEL FURNACE FOR FOAMING PELLETS TO GLASS FOAM GRANULES

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Summary

A stationary and non-stationary solution of the temperature field of the horizontal tunnel furnace for forming foam glass granules is presented. Temperature field in each zone of the furnace is obtained using the tools of the software package MAGMA5. The heat loss to the environment and heat capacity of the foaming material are taken into account. Specific solutions are obtained which carry out the appropriate optimum temperature regime for the different stages of the process – forming, fixing, tempering and cooling. A detailed study of the kinetics of foam glass formation in the single pellet is presented too. A solution for temperature field in the pellet during the process of foaming is obtained and discussed. Mathematical interpretation automatically takes into account the change of the foam-glass volume and changes of any other process parameter such as mass density, thermal conductivity and others.

Key words: foam glass formation, mathematical modelling, heat-mass-transfer, tunnel furnaces

1. Introduction

Lately the foam glass granules are widely used in many areas of life and industry. Therefore, the establishment of efficient technologies for the production of such materials is becoming very important [1,2].

One of the effective tools for the development and optimization of such kind of technologies is the mathematical modelling [3,4] of processes and phenomena occurring during the formation of such granules.

In this report 3D mathematical models for temperature field in a horizontal furnace to form foam glass granules and for thermal processes in the individual granule are proposed.

2. Mathematical model of the furnace

A simple scheme of treated device is pointed on Fig.1.

![Fig.1. General View of the device](image-url)

1 Feeder device dosing pellets; 2 Heating furnace; 3 Fixing section; 4. Tempering section; 5. Vents. 6; Transport mesh; 6 Continuous steel net; 7. Cleaning device; 8. Receiving module on the formed granules.
For the purposes of mathematical modelling the main part of furnace participate in the heat transfer are built in 3D using software package MAGMAS5\(^5\) and is shown on Fig. 2.

The 3-dimensional heat transfer equation is used in each material environment

\[
\frac{\partial (c_p \rho T)}{\partial t} = \text{div}(\lambda \text{grad}(T))
\]

where
- \(c_p\) - specific heat capacity of the material;
- \(\rho\) - mass density of the material;
- \(\lambda\) - coefficient of conductivity;
- \(T(x,y,z,t)\) – temperature field.

To equation (1) should be added to the appropriate boundary conditions as follows

1. On the boundary between working sections 3&4 (Fig.2) and the insulation

\[
- \lambda_{ins} \frac{\partial T_{ins}}{\partial n} = -\lambda_{ws} \frac{\partial T_{ws}}{\partial n} = \alpha_{ws-ins} (T_{ws} - T_{ins})
\]

where
- \(\lambda_{ins}, \lambda_{ws}\) - coefficients of conductivity of the relevant material environment;
- \(\alpha_{ws-ins}\) - heat transfer coefficient of the same boundary;
- \(T_{ins}, T_{ws}\) - temperatures on contacted surfaces.

2. Boundary condition describing the heating of the working areas with convection and radiation

\[
q_i = \alpha_c (T_h - T_{av}) + \sigma[T_h^4 - (T_{av})^4]
\]

where
- \(q_i\) - heat flux transferred from the heater to the working environment;
- \(T_h\) - heater’s temperature;
\( T_{w}^{av} \) - average temperature of the working environment;
\( \alpha_{c} \) - heat transfer coefficient of convection;
\( \sigma \) - the coefficient of radiation exchange.

4. Boundary condition describing the heat transfer from the furnace to the environment

\[
q_{env} = \alpha_{wall} (T_{wall} - T_{A}) = -\lambda_{ins} \frac{\partial T_{ins}}{\partial n} \bigg|_{wall},
\]

where
\( q_{env} \) - heat flux transferred from external walls to the environment;
\( \alpha_{wall} \) - heat transfer coefficient of the convection to the environment;
\( T_{wall} \) - temperature on the external surface of the walls;
\( T_{A} \) - ambient temperature.

The heat loss may be obtained by adding together all the heat flows towards the environment. They give the following amount

\[
W_{a} = \sum_{i=1}^{11} \int_{S_{i}} \alpha_{c}[T(S_{i})][T(S_{i}) - T_{A}]d\sigma_{i},
\]

where with \( S_{i} \) surrounding surfaces are denoted.

3. **Mathematical model for temperature field during the foaming**

The used pellets have a spherical form. In this case the equation (1) will transform into the next equation

\[
\frac{\partial}{\partial t} (\rho c_{p}T(r,t)) = \lambda_{s} \left( \frac{\partial^{2} T(r,t)}{\partial r^{2}} + \frac{2}{r} \frac{\partial T(r,t)}{\partial r} \right), \quad t > 0, 0 < r < R_{o},
\]

where \( R_{o} \) is the radius of the pellet. When the temperature in the pellet exceeds 650\(^{\circ}\)C the foaming process starts and the volume of pellets increases. Let we denote the change of the radius \( R_{o} \) with the follow monotonically increasing function

\[
R = F(t),
\]

where \( R_{o} = F(t_{650}) \).

When the temperature of the pellet exceeds 650\(^{\circ}\)C the task is solved as a task with moving boundary – the surface of the sphere. The pellet is heated in condition of gas convection and radiation therefore the boundary condition looks like the follow equation

\[
\lambda_{p} \frac{\partial T}{\partial r} \bigg|_{S} = \alpha_{c}[T_{ws} - T_{p}(R,t)] + \sigma[T_{h}^{4} - T_{p}(R,t)^{4}],
\]

where
\( S \) - surface of the sphere;
\( \lambda_{p} \) - coefficient of conductivity of the pellet and granule;
\( T_{p} \) - temperature field of the pellet and granule;
\( \alpha_{c} \) - heat transfer coefficient of gas convection;
\( T_{ws} \) - the average temperature of air in heating section.
4. Obtained results and discussions

4.1. Temperature regime of the furnace

After appropriate discretization of the geometry of the furnaces with the mesh generator of MAGMAsoft a solution of the model mentioned in sec.2 is obtained with the slower of the same software. The temperature field of the working sections are shown on Fig.3 in colour-code presentation.

![Fig.3. Temperature field of working sections of the furnace](image)

On the next figure (Fig.4) the planet temperature distribution is compared with obtained from simulation. It can be seen that the constructive solution implemented temperature regime close to the desired. The temperature is presented in control points 5(Fig.2).

![Fig.4. Comparison between planed and model temperature distribution](image)
The calculated by formula (5) heat losses are obtained equal to 10.83kW.

4.2. Temperature field of the pellet and formed granule

The solutions of the model presented in section 3 are obtained with special software developed from authors. The temperature dependant thermo physical parameters are used taking into account the influence of volume expansion during the foaming. For this purposes the following relations are used.

For pellets:

\[ C_p = \gamma C_{Glass} + (1 - \gamma)C_{Air} \]
\[ \rho_p = \gamma \rho_{Glass} + (1 - \gamma)\rho_{Air} \]
\[ \lambda_p = \gamma \lambda_{Glass} + (1 - \gamma)\lambda_{Air} \]

For granules:

\[ C_G = \chi C_p + (1 - \chi)C_{Air} \]
\[ \rho_G = \chi \rho_p + (1 - \chi)\rho_{Air} \]
\[ \lambda_G = \chi \lambda_p + (1 - \chi)\lambda_{Air} \]

where \( \gamma = 0.7 \) from experimental investigations. \( \chi(t) = V_p/V_G(t) \) is obtained from experimental data pointed on Fig.5. The evolution of radius of granule (equation (7), sec.3) is calculated from \( R_G(t) = R_p \sqrt[3]{V_G(t)/V_p} \). The obtained data using (9) and (10) are shown on Fig.6-8 respectively.

Fig.5. Volume registration during foaming

Fig.6. \( C_p(T) \)

Fig.7. \( \rho(T) \)

Fig.8. \( \lambda(T) \)
Temperature problem for two pellets with different radiiuses ($R_p=5\text{mm}$ and $R_p=7.5\text{mm}$) is solved. The obtained main curves (minimum, maximum and average temperatures) are shows on Fig.9 and Fig.10.

It should be noted the logical faster heating of the smaller pellets and a wider zone of the foaming for the larger. On the based of these simulations it can be possible to determine the optimum speed of pellet’s transport which could be adjusted to obtain maximum performance. The second vertical red line in Fig.9 and Fig.10 gives us the optimal time for the moving of the pellets through the foaming zone.

The following two figures (Fig.11 and Fig.12) show the radial distributions of the temperature within the granules during foaming. The direction of increased radius is shown and the moments of time are marked.

The next series of figures shows the temperature field in the cross section of the granules during the foaming. Fig.13-16 show the results obtained for the pellets with size $R = 5 \text{ mm}$ while Fig.17-20 show received results for granules with size $R = 7.5 \text{ mm}$. The moments of time and temperature ranges have presented.

The impact of transport net is not reported. It is not taken into account.
Fig. 13. $R=5.5\text{mm}$ $T=648 - 666\,^\circ\text{C}$

Fig. 14. $R=6.9\text{mm}$ $T=735 - 760\,^\circ\text{C}$

Fig. 15. $R=8.2\text{mm}$ $T=844 - 852\,^\circ\text{C}$

Fig. 16. $R=10\text{mm}$ $T=856 - 859\,^\circ\text{C}$

Fig. 17. $R=7.8\text{mm}$ $T=657 - 687\,^\circ\text{C}$

Fig. 18. $R=9.6\text{mm}$ $T=714-750\,^\circ\text{C}$
Conclusion

On the based of developed mathematical models important solutions are obtained. Most of them are:

- The tasks are solved at a high level of complex conditions – process parameters depend of temperature and also from the changed geometry;
- Temperature distribution in working sections of the furnace is close to the planned one;
- An estimation of heat lost is calculated;
- Temperature problem for pellets is solved in condition of moving boundary;
- The solution of the temperature problem during foaming allows optimizing the process performance;

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