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Heat Balance Analysis of EPS Products Shaping Process

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Abstract

The work is a part of research into the reduction of energy consumption in the production of EPSthrough the modernization of technological equipment used. This paper presents the results of research and analysis of heat transfer process between the water vapor that was provided to machine, the mold, the product and the environment. The paper shows the calculation of the heat balance of the production cycle for two types of mold: standard and modernized. The performance tests used an infrared imaging camera. The results were used to develop a computer image analysis and statistical analysis. This paper presents the main stages of the production process and the construction of technological equipment used, changing the mold surface temperature field during the production cycle and the structure of the heat balance for the mold and its instrumentation. It has been shown that the modernization of construction of technological equipment has reduced the temperature field and as a consequence of decreased of demand for process steam production cycle.

Keywords: Innovative technologies and materials, Heat balance, Steam, EPS, Thermography

1. Introduction

The ongoing work is a part of research on the modernization of the production process of expanded polystyrene (EPS) in the company SchaumaPlast Organika Sp. z o. o. in Lodz. The essence of the research is to reduce the energy consumption of the manufacturing process used for the modernization of technological equipment. The modular packaging and molded polystyrene is used EPS (styrofoam). Preparation of raw material for the production takes place through the pre-expansion, in which the balls EPS due to the heat affecting the blowing agent contained in polystyrene, increase their volume to the desired density. The next stage is seasoning in silos, in which the release occurs inside of pentane already porous EPS beads. The material prepared is injected into the mold, in which by means of steam is heated and then cooled. Thus bead material increase in volume, they combine with each other and match the shape of the mold cavity of product [1, 2].

The aim of the work was to analyze the process of heat transfer between steam brought to machine, the mold, the product and the environment and also the calculation of the heat balance of the production cycle for two types of equipment: standard and modernized one.

2. Experimental

Tests were conducted on a production station of machine made by a German company Kurtz GmbH. The machine cycle consists of the following steps: closing the mold and filling material, steam entering, cooling and stabilization of the device, the deformation and removing product from the mold. In Figures

1 and 2 adequately the scheme and the view of mold tooling in a production machine was shown of a typical EPS product that is shown in Figure 3.

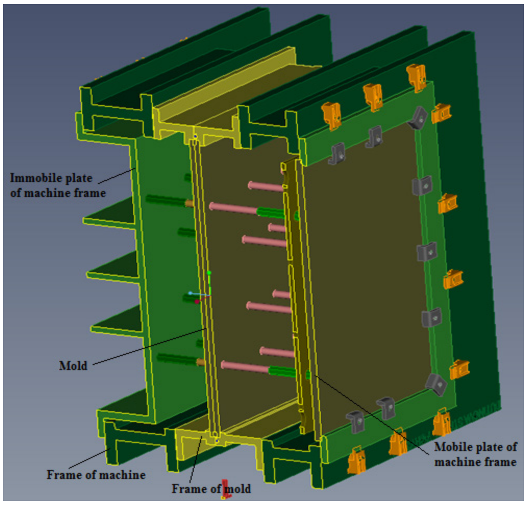

Fig. 1. Scheme of mold construction for manufacturing of EPS products

Fig. 2. Photo of mold equipment in manufacturing machine

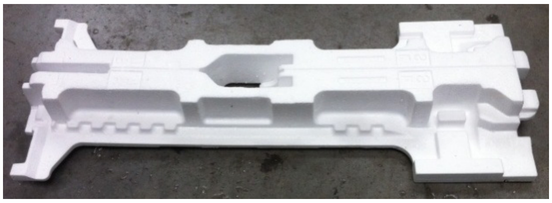

Fig. 3. Photo of EPS product

This instrumentation has a box-like structure formed by the fixed mold plate in the mold, respectively, which are installed in a immobile (Fig. 1, right side) and a movable (left) frame of the machine. Into the space existing between the plates is supplied with steam at 120 ÷ 130°C and a pressure of 0.22 ÷0.23 MPa. During the modernization of equipment the construction and the material of the immobile plate was changed from cast iron into aluminium and also the thermal insulation layer inside the aluminum frame of mold and the machine was used.

The heat balance calculation was used:

- the first law of thermodynamics

$$Q = U_2 - U_1 = h_2 - h_1 + p_2 V_2 - p_1 V_1 , \quad (1)$$

where: U_1 , U_2 - internal energy of the system, - h_1, h_2 enthalpy, p_1, p_2 , V_1, V_2 – the pressure and volume of the system in states 1 and 2,

with the change of internal energy is equal to the change in kinetic energy of the molecules and is the model

$$\Delta U = \Delta E_k = m\, c_w\, \Delta t, \quad (2)$$

where: m – weight, c_w – specific heat at constant volume,
Δt – change in temperature of the substance,

- Newton law determining the density of the heat flux exchanged between the surface of chilled and ambient:

$$q = \alpha\, (t_{pow} - t_{ot}), \quad (3)$$

where: q_{pow} - the density of the heat flux exchanged between the cooled surface and the surroundings; α – coefficient of heat transfer; t_{pow} – the temperature of the surface; t_{ot} – ambient temperature.

- Stefan-Boltzmann equation, which determines the amount of energy emitted by the formula:

$$E = \varepsilon\, C_0\, A\, T^4, \quad (4)$$

where: C_o- Stefan-Boltzmann constant, ε - surface emissivity of the substance, T – absolute temperature of the surface [3, 4].

3. Results

In Fig. 4-6 are examples of thermographic results of equipment molds respectively No. 1 and No. 2 in the process of making a styrofoam product.

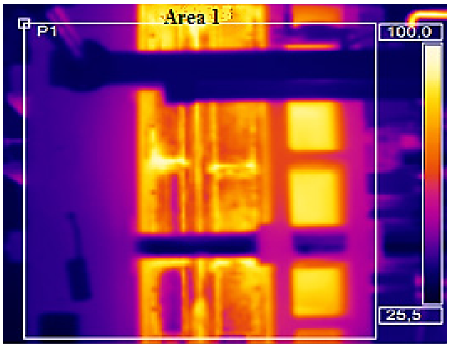

Fig. 4. Temperature field of mold equipment in manufacturing machine No. 1 – view from mold parting side

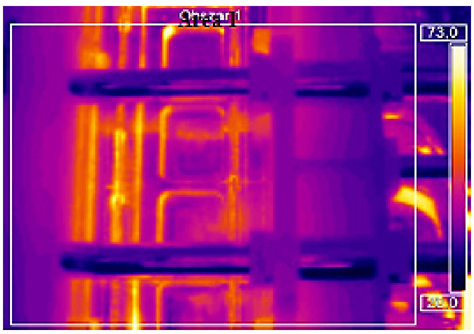

Fig. 5. Temperature field of mold equipment in manufacturing machine No. 2 – view from mold parting side

a)

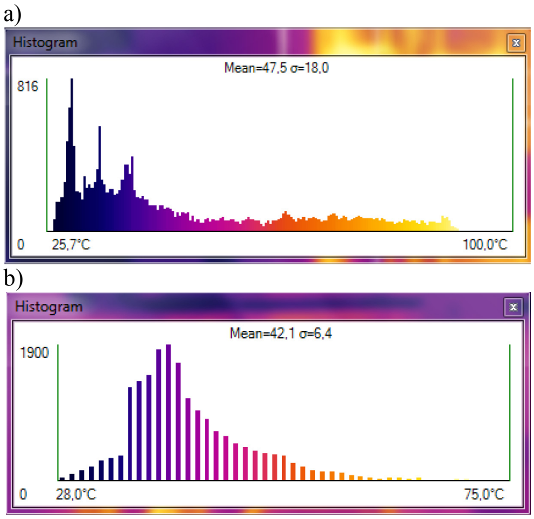

Fig. 6. Histogram of temperature field of area 1 of mold equipment in manufacturing machine: a) No. 1 (Fig.4), b) No. 2 (Fig. 5)

The research shows that the area of instrumentation molds characterized by a temperature variation of 26÷100°C for machines No. 1 and the 28÷75°C for machine No. 2, and the average value of the temperature distribution (Fig. 6), which was 47.5°C for mold equipment 1 and 42.1°C - for mold No. 2. The temperature field of the surface of the modernized mold tooling No. 2 characterized by a much higher stability, which confirms approximately 3-times reduction in standard deviation of the distribution of temperature fields examined form $\sigma = 18.0$ to $\sigma = 6.4$.

In addition, research shows that the highest range of temperature fields occurred in the framework and the immobile plate and movable mold tooling machines 1. The instrumentation after upgrading has much lower temperature and its highest range is at the surface of the mold frame around the mold parting surface.

Na podstawie przeprowadzonych na stanowiskach produkcyjnych badań i analiz opracowano równanie bilansu energii cieplnej doprowadzonej za pomocą pary wodnej opisane wzorem:

$$Q_d = Q_{fo} + Q_w + Q_{ch} + Q_{konw} + Q_{prom} + Q_k + Q_{st} \qquad (5)$$

where:

Q_d - the heat supplied to the machine by means of technological steam,

Q_w – heat received by the product material EPS during processing and removed together with the product,

Q_{fo} – change of heat accumulated by the tooling mold resulting from cyclic temperature changes,

Q_{ch} – heat received from the mold by cooling water spray,

Q_{konw} – heat absorbed by the surroundings due to convection,

Q_{prom} – heat radiated by the mold tooling environment,

Q_k – heat discharged from the condensate - water resulting from the cooled steam for instrumentation,

Q_{st} – loss of steam caused by such stabilization of the vacuum, venting and leakage mold.

Table 1 shows the values of physical constants and the values of the parameters used to calculate the components of heat consumed in the researched process of the molds equipment of machine No. 1 and No. 2. Quantity of steam was based on heat meter installed at the inlet steam to the plant. Enthalpy and specific volume of water vapor was determined on the basis of the graph of enthalpy - entropy [5]. Analysis of product design and tooling provided data on the mass and geometry of its components. The values of temperature of the components involved in the heat exchange of water vapor with the surrounding equipment specified on the basis of statistical analysis of variability in time of the production cycle instrumentation temperature fields examined using an infrared camera.

Table 2 shows the calculation formulas developed on the basis of knowledge of the subject of study for components of the heat balance [4-6].

The developed models includes among others cyclic heat consumption for raising the temperature cooled-tooling components freely and forcibly cooled in a shower of water (Tab. 2, No. 2, 4 and 6) and a blowing agent in the evaporation heat-formed article. In addition, it's developed a model to calculate the heat demand during the start-up of steam production machine (Q_{rozr}, Table 2: No. 9), which are consumed every day as planned working time in the company.

Table 3 shows the results of components calculations of the balance of heat energy supplied to the machine in the form of technological steam by the formulas shown in Tab. 2. These results are shown in Fig. 7 as a plot of the percentage calculated balance components charged to the heat delivered to the machine Q_d at the time of the production cycle.

Presented in Tab. 3 the summary of research results shows that modernization of mold equipment in the machine No. 2 decreases from 6943.6 kJ to 5552.1 kJ or about 20% of the demand for heat which is supplied to the machine during the manufacturing cycle of products. In addition, calculations show that the heat energy lost during machine startup is about four times the demand for heat during the manufacturing cycle.

Table 1.
Values of physical constants and calculation parameters for researched mold equipment

	Constant or parameter name, symbol	Unit	Machine No. 1	Machine No. 2
1	Consumption steam in production cycle, m_z	kg	2.495	1.995
2	Entalphy of steam , h	kJ/kg	2720	2720
3	Pressure of delivered steam, p_2	MPa	0.09	0.09
4	Specific volume , V_1	m^3/kg	0.7	0.7
5	Specific heat of water , c_w	kJ/(kgK)	4.19	4.19
6	Specific heat of product material , c_{ps}	kJ/(kgK)	1.5	1.5
7	Heat of vaporization of blowing agent, $c_{par\text{-}porof}$	kJ/kg	336.27	336.27
8	Specific heat of frame material (Al), $c_f = c_{rf} = c_{rm} = c_{prmr}$	kJ/(kg K)	0.91	0.91
9	Specific heat of plate material, $c_{prms} = c_{Zl}$ lub c_{Al}	kJ/(kg K)	0.48	0.91
10	Heat transfer coefficient , α	$W/(m^2K)$	30	30
11	Stefan – Boltzmann constant, C_0	$W/(m^2 \cdot K^4)$	5.67E-08	5.67E-08
12	Emissivity of elements surface Al, ε_{Al}		0.65	0.65
13	Emissivity of machine surface, ε_m		0.95	0.95
14	Product weight, m_w	kg	0.59	0.46
15	Mass of steam condensate received from the mold, m_k	kg	0.75	0.75
16	Mass of steam condensate in product, m_{wps}	kg	0.018	0.016
17	Mass of mobile and im mobile part of mold, $m_{fr} + m_{fs}$	kg	131	131
18	Mold frame weight, $m_{rfs} + m_{rfr}$	kg	101	101
19	Machine frame weight, $m_{rms} + m_{rmr}$	kg	106	106
20	Machine immobile plate weight, m_{prms}	kg	294	64
21	Machine mobile plate weight, m_{prmr}	kg	64	64
22	Blowing agent part in product weight, -		0.05	0.05
23	Time of cycle, τ	s	52	80
24	Surface of mold frame, A_{rf}	m^2	1.3	1.3
25	Surface of machine frame, A_{rm}	m^2	1.73	1.73
26	Surface of machine plate, A_{pm}	m^2	1.23	1.23
27	Surface of mold plate, A_{pf}	m^2	0.63	0.63
28	Temperature of delivered steam , t_{pary}	°C	125	125
29	Temperature of mold, t_f	°C	95.5	95.5
30	Temperature of frame mold surface, t_{powrf}	°C	90.8	52
31	Temperature of machine mold surface, t_{powrm}	°C	49.8	41.6
32	Temperature of machine plate surface, t_{powpm}	°C	93.7	65
33	Temperature of mold plate surface, t_{powpf}	°C	93.6	73
34	Temperature of raw material, t_o	°C	26	26
35	Temperature of product removed from the mold, t_w	°C	87	87
36	Increase of mold temperature, $t_{fk} - t_{fp}$	°C	16	9
37	Temperature rise of the mold frame, $t_{rfk}-t_{rfp}$	°C	3.3	5.1
38	Temperature rise of the machine frame, $t_{rmk} - t_{rmp}$	°C	2.9	2.8
39	Temperature rise of the machine plate, $t_{pmsk} - t_{pmsp}$	°C	2.4	2.6
40	Temperature rise of the mobile plate, $t_{prmrk} - t_{prmrp}$	°C	4.7	2.5
41	Mold temperature decrease during cooling, $t_{fchp} - t_{ochk}$	°C	18.9	18.9
42	Product temperature decrease during cooling, $t_{wp} - t_{wk}$	°C	42	42

Table 2.
Calculation formulas of balance heat components

	Calculation formulas
1	$Q_d = m_z\, h + p_2\, V_1$
2	$Q_{fo} = (m_{fs} + m_{fr})\, c_f\, (t_{fk} - t_{fp}) + (m_{rfs} + m_{rfr})\, c_{rf}\, (t_{rfk} - t_{rfp}) + (m_{rms} + m_{rmr})\, c_{rm}\, (t_{rmk} - t_{rmp})$ $+ m_{prms}\, c_{prms}\, (t_{pmsk} - t_{pmsp}) + m_{prmr}\, c_{prmr}\, (t_{prmrk} - t_{prmrp})$
3	$Q_w = m_w\, [0{,}05\, c_{par\ porof} + c_{ps}\, (t_w - t_o)]$
4	$Q_{ch} = m_f\, c_f\, (t_{fchp} - t_{ochk}) + m_w\, c_{ps}\, (t_{pp} - t_{pk})$
5	$Q_k = (m_{wk} + m_{wps})\, c_w\, (t_w - t_o)$
6	$Q_{konw} = \alpha\, \tau_c\, [(t_{powrf} - t_{ot})A_{rf} + (t_{powrm} - t_{ot})A_{rm} + (t_{powpm} - t_{ot})A_{pm} + (t_{powpf} - t_{ot})A_{pf}]$
7	$Q_{prom} = C_0\{\varepsilon_{Al}\, [A_{rf}\, (T_{rfk})^4 + A_{pfr}\, (T_{prmrk})^4] + \varepsilon_m\, [A_{rm}\, (T_{rmk})^4 + A_{pm}\, (T_{pmsk})^4]\}$
8	$Q_{st} = Q_d - Q_{fo} - Q_w - Q_{ch} - Q_k - Q_{konw} - Q_{prom}$
9	$Q_{rozr} = (m_{fs} + m_{fr})\, c_f\, (t_{fk} - t_{ot}) + (m_{rfs} + m_{rfr})\, c_{rf}\, (t_{rfk} - t_{ot}) + (m_{rms} + m_{rmr})\, c_{rm}\, (t_{rmk} - t_{ot})$ $+ m_{prms}\, c_{prms}\, (t_{rmk} - t_{ot}) + m_{prmr}\, c_{prmr}\, (t_{prmrk} - t_{ot})$

Table 3.
Results of calculation of balance heat components

	Component	Unit.	Machine No. 1	Machine No. 2
1	Q_d	kJ	6943.585	5552.085
2	Q_{fo}	kJ	3102.813	2108.743
3	Q_w	kJ	605.118	471.787
4	Q_{ch}	kJ	2290.239	2282.049
5	Q_k	kJ	196.293	195.782
6	Q_{konw}	kJ	391.986	332.083
7	Q_{prom}	kJ	3.468	2.645
8	Q_{st}	kJ	353.668	158.996
9	Q_{rozr}	kJ	30027.459	17188.171

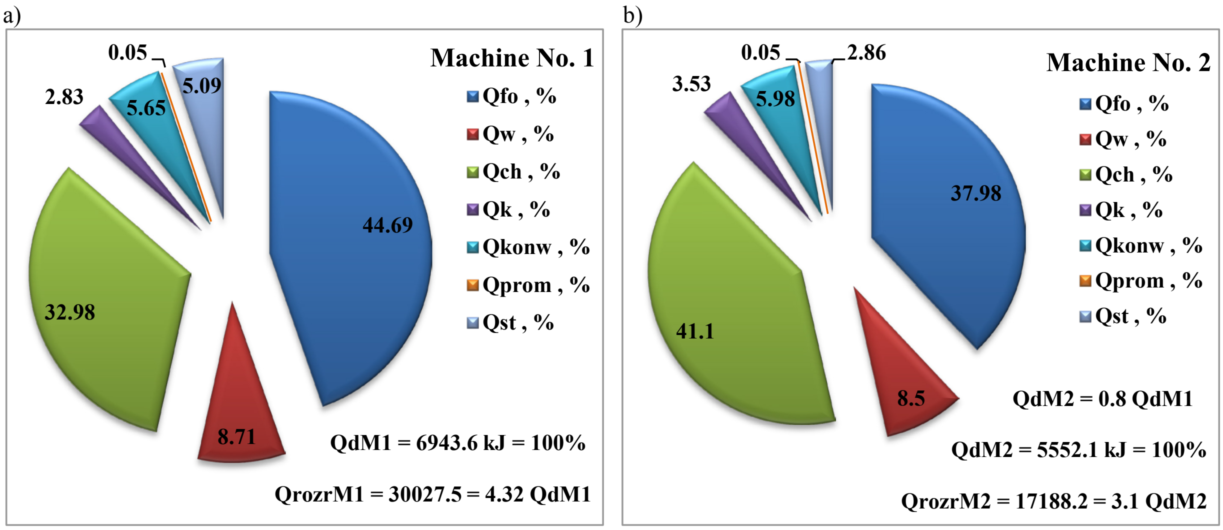

Fig. 7. Comparison of heat balance percentage components of mold equipment for machine: a) – No. 1, b) – No. 2

The heat balance shows that the largest part of the heat input is consumed for cyclic heating of molds equipment and heat received from the mold during the cooling spray of water. These components are about 5 times greater than the heat absorbed by the material during processing, and removed together with the product Q_w.

A comparison of the percentage of heat balance that mold equipment machine No. 2 is characterized by a reduced part of heat cyclic heating of instrumentation elements Q_{fo} and twice lower rate of heat loss Q_{st} caused by a temperature stability of mold, venting and leakage mold tooling.

4. Conclusions

The main conclusions of the work are as follows:

- modernization of mold equipment in the machine No. 2 decreased about 20% the heat energy requirement during the production cycle, and 2-times reduced heat losses caused by the mold temperature stability and leaking equipment,
- the largest part of the heat input is consumed in the molds for cyclic heating of equipment and it is five times greater than the heat absorbed by the material processed and removed together with the product from the mold,
- heat energy consumed during machine startup is about four times greater than the heat demand in the production cycle.

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