A NEIGHBORHOOD MODEL OF A STATION FOR MAINTAINING POLYOL OPTIMUM TEMPERATURE

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ABSTRACT

The possibility of applying the neighborhood model to control the station of maintaining polyol optimum temperature is investigated. State and control act as parameters. The identification of the model, the thermotechnical calculation and the combined control of the neighborhood model for determining the heat transfer coefficient are performed. The obtained values of the heat transfer coefficient are compared.

Keywords: neighborhood system, identification, combined control, polyol, heat exchanger, heat transfer coefficient.

INTRODUCTION

The chemical industry uses polyol as an additive in the production of new generation polyurethane foams. Polyol makes it possible to significantly improve the quality of finished products, viz., the bearing capacity and elasticity of foam, to improve the quality of its processing technology, to increase the service life and appearance of products. In addition, polyol allows the regulation of the physical and mechanical properties of polyurethane foams [1, 2].

Polyurethane foam production is peculiar in that it provides the possibility of foaming and solidification of polyol at a temperature of about +20°C, thus it is necessary to maintain polyol temperature in a given range above this value.

The production of materials and products on the ground of polyol requires an optimum temperature which is maintained by heat exchangers of definite heat transfer coefficients. It is common to perform thermotechnical calculation in designing and selecting heat exchangers. Polyol is usually heated with shell-and-tube heat exchangers. Polyol flows inside horizontal cylindrical tubes, while the heating agent flows transversely to the tubes in the intertubular space in several strokes.

The heat transfer coefficient is a variable, since the temperature of initial polyol and of the heating agent, as well as their consumption may change during polyurethane foam production. In this regard, it is necessary to determine rapidly the value of the heat transfer coefficient in the system of controlling the process of heating and maintaining the set temperature.

The determination of the heat transfer coefficient through thermotechnical calculation is a precise, but quite time-consuming process, as it involves a lot of calculation formulas. The application of neighborhood models provides the acceleration and simplification of this process with sufficient precision of its control.

The aim of this paper is to demonstrate a technique for a simple and rapid determination of the heat transfer coefficient of a heat exchanger by applying neighborhood models when one of the heating agents is a high viscosity liquid and to compare the obtained results with those of thermotechnical calculation.

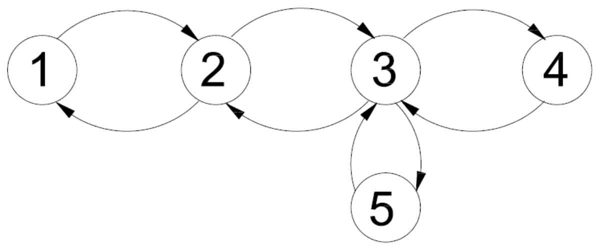

Fig. 1. A graph of a station for maintaining polyol optimum temperature.

MATHEMATICAL MODEL

The structural model of a station for maintaining polyol optimum temperature can be conditionally represented as five main nodes whose relationship is graphically presented in Fig. 1. There 1 stands for the polyol storage container, 2 – for the polyol transfer pump, 3 – for the heat exchanger, 4 – the polyol consumer, while 5 – for the refrigerator.

The bilinear neighborhood model of a station for maintaining polyol optimum temperature has the form [3, 4]:

$$w_x[1,1]\cdot x[1]+w_x[1,2]\cdot x[2]+w_v[1,1]\cdot v[1]+$$
$$+w_v[1,2]\cdot v[2]+w_{xv}[1,1,1]\cdot x[1]\cdot v[1]+$$
$$+w_{xv}[1,1,2]\cdot x[1]\cdot v[2]+w_{xv}[1,2,1]\cdot x[2]\cdot v[1]+$$
$$+w_{xv}[1,2,2]\cdot x[2]\cdot v[2]=0;$$

...

$$w_x[5,3]\cdot x[3]+w_x[5,5]\cdot x[5]+w_v[5,3]\cdot v[3]+$$
$$+w_v[5,5]\cdot v[5]+w_{xv}[5,3,3]\cdot x[3]\cdot v[3]+$$
$$+w_{xv}[5,3,5]\cdot x[3]\cdot v[5]+w_{xv}[5,5,3]\cdot x[5]\cdot v[3]+$$
$$+w_{xv}[5,5,5]\cdot x[5]\cdot v[5]=0$$

The essential components for state and control are presented in Table 1.

According to the technological parameters of the station for maintaining polyol optimum temperature, the values of the state and control components are:

x[1]=40°C,	v[1]=22 tons,
x[2]=13.2 tons/day,	v[2]=319 rpm,
x[3]=71.2 W/(m^2·K),	v[3]=22 °C,
x[4]=22 °C,	v[4]=11,9 tons/day,
x[5]=5 °C,	v[5]=27.5 tons/day.

Due to the different order of the input data, the normalization is separately performed for the state and control components [5, 6]:

$$x' = \frac{x - \overline{x}}{\sigma},$$

where x is the normalized value, $\overline{x}$ is the arithmetic average, while σ is the mean square deviation of values.

As a result, the following values are obtained:

x'[1]=0.41309;	v'[1]=-0.49013;
x'[2]=-0.72588;	v'[2]=1.99824;
x'[3]=1.73906;	v'[3]=-0.49013;
x'[4]=-0.35189;	v'[4]=-0.57392;
x'[5]=-1.07438;	v'[5]=-0.44405.

As a result of the identification, the following values of the coefficients of the model equation are obtained:

Table 1. Components of state and control.

x[1]	Polyol temperature in the storage container, °C
x[2]	Polyol consumption, tons/day
x[3]	Heat transfer coefficient of the heat exchanger, W/(m^2·K)
x[4]	Temperature of polyol transferred to the consumer, °C
x[5]	Temperature difference of the heating agent before and after the heat exchanger, °C
v[1]	Polyol reserve in the storage container, tons
v[2]	Rotation speed of the pump shaft, rpm
v[3]	Polyol temperature after the heat exchanger, °C
v[4]	Consumption of polyol transferred to the consumer, tons/day
v[5]	Heating agent consumption, tons/day

$w_x[1,1]=-1.32065$; $w_x[1,2]=-0.03573$; $w_v[1,1]=-0.325$; $w_v[1,2]=0.09835$; $w_{xv}[1,1,1]=0.00996$; $w_{xv}[1,1,2]=0.04063$; $w_{xv}[1,2,1]=0.01751$; $w_{xv}[1,2,2]=-0.08411$;...
$w_x[5,3]=-0.52098$; $w_x[5,5]=-1.61637$; $w_v[5,3]=0.14683$; $w_v[5,5]=0.47534$; $w_{xv}[5,3,3]=0.25535$; $w_{xv}[5,3,5]=0.23134$; $w_{xv}[5,5,3]=-0.15775$; $w_{xv}[5,5,5]=-0.14292$.

METHODS OF THERMOTECHNICAL CALCULATION

The thermotechnical calculation consists of finding the heat transfer coefficient of the heat exchanger proceeding on the ground of a set of values of polyol and heating agent consumption and the temperature difference between polyol and the heating agent prior to and after the heat exchanger, while the thermal balance must be observed:

$$Q = G_{pol} \cdot c_{pol} \cdot \Delta t_{pol} = G_{hc} \cdot c_{hc} \cdot \Delta t_{hc}$$

where Q is the amount of heat (W), G_{pol} is the polyol consumption (kg/s), c_{pol} is the polyol heat capacity (J/kg K) [7], Δt_{pol} is the temperature difference of polyol before and after the heat exchanger (°C), G_{hc} is the heating agent consumption (kg/s), c_{hc} is the heat capacity of the heating agent (J/(kgK), while Δt_{hc} is the temperature difference of the heating agent prior to and after the heat exchanger (°C).

Water is used as a heating agent.

The average flow velocity of polyol is determined as:

$$w_{pol} = \frac{4 \cdot G_{pol}}{\rho_{pol} \cdot n \cdot \pi \cdot d_{in}^2}$$

where w_{pol} is the average flow velocity of polyol (m/s), ρ_{pol} is the polyol density (kg/m^3) [7], n is the number of tubes, while d_{in} is the inner diameter of tube (m).

The Reynolds number for polyol [8, 9] is:

$$Re_{pol} = \frac{w_{pol} \cdot d_{in}}{\text{í}_{pol}},$$

where ν_{pol} is the kinematic viscosity of polyol (m^2/s) [7].

The Grashof number for polyol [8, 9] is:

$$Gr_{pol} = \frac{g \cdot d_{in}^3 \cdot \beta_{pol} \cdot \Delta t_{pol}}{\nu_{pol}^2},$$

where g is the gravitational acceleration (m/s^2), while β_{pol} is the coefficient of cubical expansion of polyol (K^{-1}) [7].

The Rayleigh number for polyol [8, 9] is:

$$Ra_{pol} = Gr_{pol} \cdot Pr_{pol},$$

where Pr_{pol} is the the Prandtl number for polyol [7].

The calculations results in Reynolds number value less than 2,300, while the Rayleigh number is higher than 800,000. This corresponds to the viscous-gravitational flow mode. Then the criterial equation will have the form [10]:

$$Nu_{pol} = 0{,}15 \cdot Re_{pol}^{0{,}33} \cdot Pr_{pol}^{0{,}33} \cdot Ra_{pol}^{0{,}1} \cdot \left(\frac{Pr_{pol}}{Pr_w}\right)^{0{,}25} \cdot \varepsilon_1$$

where Pr_w is the Prandtl number for polyol at tube wall temperature [7], ε_l is the correction factor with account of the influence of the flow hydrodynamic stabilization process on the heat transfer in the initial section of heat exchange [10].

The heat transfer coefficient of polyol is [8, 9]:

$$\alpha_{pol} = \frac{Nu_{pol} \cdot \lambda_{pol}}{d_{in}},$$

where α_{pol} is the heat transfer coefficient of polyol (W/(m^{2}K), λ_{pol} is the polyol thermal conductivity (W/(mK) [7].

The average flow velocity of the heating agent is defined as:

$$w_{hc} = \frac{G_{hc}}{\rho_{hc} \cdot F_{hc}}$$

where w_{hc} is the the average flow velocity of the heating agent (m/s), ρ_{hc} is the heating agent density, (kg/m^3), while F_{hc} is the average flow surface area (m^2). The latter is described by:

$$F_{hc} = \frac{D}{2} \cdot \frac{l}{z} - F_t,$$

where D is the diameter of heat exchanger shell (m), l is the length of heat exchanger (m), z is the number of strokes in the heating agent, while F_t is the average surface area of the tubes that limit the heating agent flow (m^2).

The Reynolds number for the heating agent [8, 9] is:

$$Re_{hc} = \frac{w_{hc} \cdot d_{out}}{í_{hc}},$$

where d_{out} is the outer diameter of the tube (m), while ν_{hc} is the kinematic viscosity of the heating agent (m^2/s).

The calculations result in Reynolds number values in the range from 100 to 1,000. According to ref. [11], the heat transfer of beams with a large and moderate longitudinal pitch is equal at such Reynolds numbers to the heat transfer of a single tube, the criterion equation for which has the form:

$$Nu_{hc} = 0{,}52 \cdot Re_{hc}^{0,5} \cdot Pr_{hc}^{0,36} \cdot \left(\frac{Pr_{hc}}{Pr_w}\right)^{0,25},$$

where Pr_w is the Prandtl number for a heating agent at a tube wall temperature.

The heat transfer coefficient of the heating agent is [8, 9]:

$$Re_{hc} = \frac{w_{hc} \cdot d_{out}}{\nu_{hc}}$$

where α_{hc} is the heat transfer coefficient of the heating agent ($W/(m^2K)$, while λ_{hc} is the thermal conductivity of the heating agent (W/(mK).

The heat transfer coefficient of the heat exchanger is: [8, 9]:

$$K = \frac{1}{\left(\frac{1}{\alpha_{pol} d_{in}} + \frac{1}{2\lambda_w} \cdot \ln\frac{d_{out}}{d_{in}} + \frac{1}{\alpha_{hc} d_{out}}\right) \cdot \frac{d_{in} + d_{out}}{2}}$$

where K is the the heat transfer coefficient of the heat exchanger ($W/(m^2K)$, while λ_w is the thermal conductivity of tube wall, (W/mK).

The results of the thermotechnical calculation are shown in Figs. 2 - 4.

RESULTS AND DISCUSSION

The heat transfer coefficients of the heat exchanger determined in the course of the thermotechnical calculation are compared with the results obtained via the combined control technique [12]. At a combined control, a part of the state and control parameters are specified, while the remaining parameters are to be determined following the minimum condition for the mean-square deviation of the neighborhood model [13]:

$$\sqrt{\frac{\sum_{i=1}^{n} (F_i)^2}{n}} \to \min,$$

where F_i is the equation for the i-th node of the system,

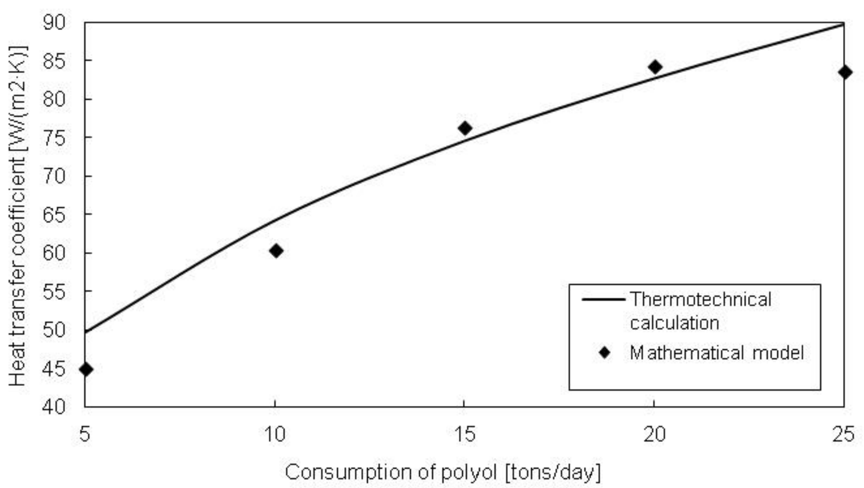

Fig. 2. Dependence of the heat transfer coefficient on polyol consumption at the value of the heating agent temperature difference x[5] = 5°C.

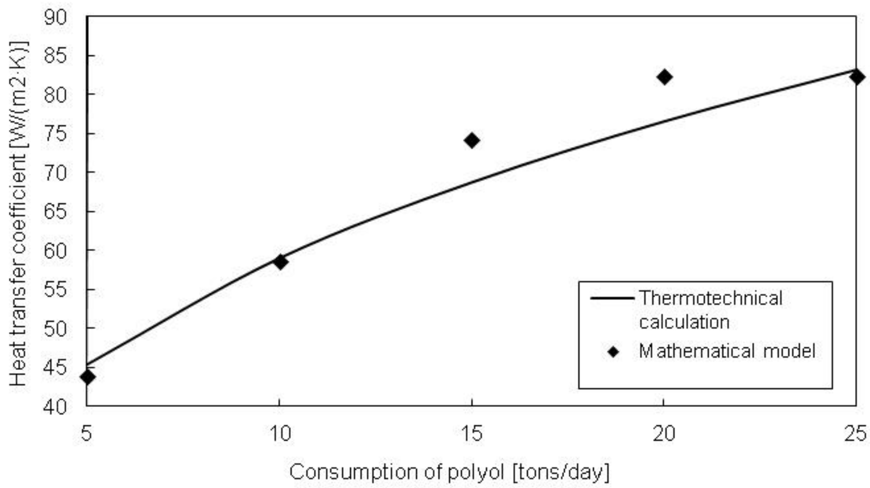

Fig. 3. Dependence of the heat transfer coefficient on polyol consumption at the value of the the heating agent temperature difference x[5] =10°C.

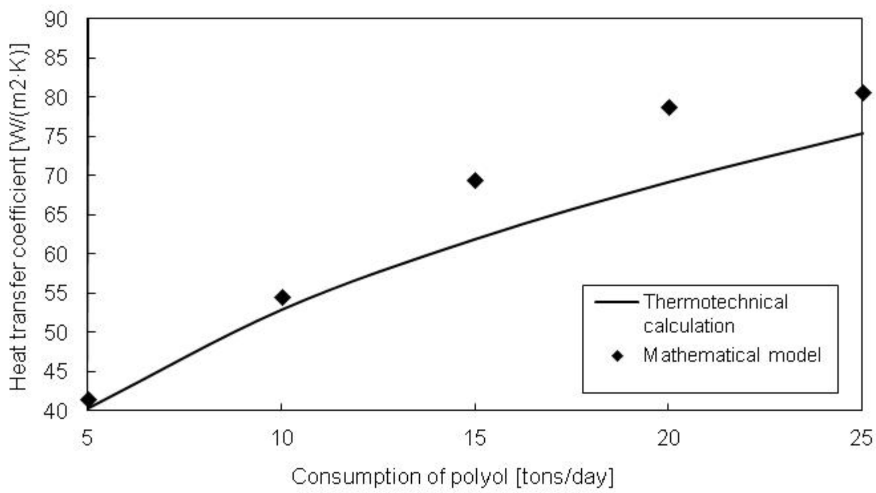

Fig. 4. Dependence of the heat transfer coefficient on polyol consumption at the value of the the heating agent temperature difference x[5] = 20°C.

while n is the number of equations corresponding to the number of nodes in the system.

For the combined control of the neighborhood model of the installation maintaining the optimum polyol temperature, the components x[1], x[2], x[4], x[5], v[1], v[3] are assumed to be given. The values of some of them corresponded to the nominal one. They do not change in the process of a mixed control:

x[1] = 40°C, v[1] = 22 tons,

x[4] = 22°C, v[3] = 22°C.

The components x[3], v[2], v[4], v[5] are determined.

The results referring to the heat transfer coefficient determination using a combined control are shown in Figs. 2 - 4.

Criterial equations for determining the heat transfer coefficient have an error of the order of ±10 % - 15 % [14]. Most of the values of the heat transfer coefficient determined as a result of a combined control do not exceed this error, which indicates the possibility of using neighborhood systems for modeling and controlling stations for maintaining polyol optimum temperature.

CONCLUSIONS

A technique for determining the heat transfer coefficient with the help of neighborhood models is demonstrated in this paper. The values of the heat transfer coefficient obtained in the process of a combined control correspond to the values obtained by thermotechnical calculation. In this connection, it becomes possible to widely apply neighborhood systems for modeling and controlling stations of this kind.

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