FEATURES OF MATHEMATICAL MODELING OF THE FIRST STAGE OF PAPER WEB DRYING

Anatolii I. Zhuchenko[1], Yevhenii S. Cheropkin[1], Ruslan A. Osipa[1] and Bogdan Y. Korniyenko[2]
[1]Department of Chemical Production Automation, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
[2]Department of Automation and Control in Technical Systems, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
E-Mail: bogdanko@i.ua

ABSTRACT

This paper is devoted to the consideration of mathematical modeling of heating processes occurring in the drying section of paper-making machine. The main attention is paid to the thermal processes issue occurring at the first stage of paper web drying, the heating. An algorithm for calculating the paper temperature change during its passage through drying cylinders and areas of free movement has been developed. The basic equations for calculating temperature of contact and central layers of the paper web are derived. The formulas for calculation auxiliary parameters of the process are given in the paper. The generalization of the obtained data in the resulting formulas form of the convective and contact periods of the paper web heating is executed. Using the statistical criteria of Student and Fisher, the check for the adequacy of the proposed mathematical model suits the actual working process has been made. The developed mathematical model will be used for simulation modeling of automatic control systems of this process.

Keywords: mathematical modeling, drying of a paper web, temperature of a paper, drying cylinder, criteria of adequacy, heat transfer, thermal balance.

INTRODUCTION

Paper web drying refers to continuous and fleeting processes, which are integral parts of the complex paper producing technological process on a paper-making machine (PMM).

As a result of the technological process analysis, it has been found that, the drying part of each PMM has its structural and technological features, despite its similarity. The features of its structure depend mainly on the type of paper to be manufactured.

This specificity, in the case of solving the problem of creating a mathematical model for a particular drying section, imposes significant restrictions on its versatility and further use and therefore is inappropriate. As practice shows [1], in such cases it is expedient to develop an adaptive mathematical model that can be adapted to the conditions and limitations of changing technological parameters and features of production.

The analysis of existing solutions has shown that in work [2] it is proposed to use the approximate simulation method of the heat transfer process on the PMM drying cylinder. The technique essence is a given structure of the model, which provides a single structure for all stages of drying. However, as other researches have shown[3-5], the physics of the heat and mass transfer process varies at different process stages of moisture and heat transfer (diffusion, filtration and filtration diffusion type of transfer), and the generalized model can be used only for an approximate calculation [6]. Therefore, more detailed consideration of this technological process is necessary at every stage.

In works [7-9], the authors show the constructed mathematical models of a paper web drying according to the works of A. A. Lukov. [3]. In contrast to the provisions given in [2], they consider the drying process, divided into stages, and models are constructed for each of them that correspond to the heat and mass transfer laws, which take place at a certain moment. The mathematical model is presented in the work [9] in the form of a differential equations system, as well as their analytical solution is shown. The drying contact and convection parts are separately considered by the authors. Another advantage of these models is the substantiation of the type of temperature gradient and moisture content in the thickness in the form of a parabola. It is assumed in these works that at the end of drying the values of temperature and humidity will be the same throughout the thickness of the paper. This statement didn't always correspond to reality, which was shown in works [3, 11]. It can only be used in the case of using thin paper types. For a thicker material, when using such mathematical models, it is necessary to calculate the parameters for the paper thickness. In the analysis of works [12-14] it is evident that a large number of data obtained complicate their analysis andare going to affect the performance of the control system negatively.

Detailed consideration is needed to be analyzed due to the results of each drying stage analysis for the task to develop a new mathematical model. Such model will allow us to get the material temperature and humidity at any time in the key points (taking into account the paper thickness).

In this paper, the mathematical modeling peculiarities of the paper web at first drying stage (a stage of heating) will be considered.

The solution of this problem will be presented as an improvement according to existing mathematical models [2, 7-9] of paper web drying, taking into account the process features of heating the paper web.

VOL. 15, NO. 5, MARCH 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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THE PURPOSE OF THE WORK

The article shows the general identification algorithm of the first stage of paper web drying.

PROCESS FEATURES OF PAPER WEB HEATING

Passing through the machine drying part, the moist paper web envelops lateral surface part of the heated cylinders, perceives heat, heats and moisture evaporates from it. The heat transfer from the heated surface of the cylinders is carried out by direct contact - contact or conduction to the paper web. In the area of free run between cylinders, the material of the sheet contacts with the surrounding air, resulting in intense evaporation of moisture due to heat accumulated in a paper web on the cylinder and heat exchange with the environment.

The moisture in the material is displaced in the liquid and vapor form presenting a saturated and unsaturated porous structure layer near the heating surface [3]. Therefore, the processes of heat and mass transfer will be different. The intensity of contact-convective paper drying is determined by external and internal processes conditions, depending on which material the following mechanisms of heat and mass transfer occur: diffusion, filtration and filtration-diffusion. The specific mechanisms of heat transfer and steaming operate at each drying stage. These mechanisms are described by different differential equations.

During heating of the paper web process the transfer of heat and mass proceeds through the diffusion mechanism.

In the case of consideration heat and mass transfer processes on the cylinders and in the areas of free movement, the air parameters in the inter cylinder spaces, the speed of the web, the diameter and temperature of the surface of the drying cylinders should be taken into account. The processes proceeding intensity is determined, mainly, by the heat transfer between the paper web and the heated drying cylinders and the surrounding air.

At the drying paper stage on multi-cylinder plants, the unsteady heat of mass transfer is primarily due to the periodicity of the contact of the wet material with the heated cylinders and ambient air, as well as the periods of drying of moist materials. That is why it is expedient to calculate the kinetics of heat and mass transfer of contact-convective units in cycles, which includes the duration of the stay of the web on the heating surface of the cylinder τ_c and in the free movement region τ_{fm} (Figure-1). Point 1 is the moment of contact of a paper web with a drying cylinder (DC); point 2 - the output of a paper web from the DC; at this moment the temperature of the paper is maximal; at the same time, this point is the beginning of the paper's stay in the area of free movement; point 3 - the end of it, the minimum temperature of the paper web, the beginning of its contact with the subsequent drying cylinder.

STAGES OF CALCULATING MATHEMATICAL MODEL OF PAPER WEB DRYING

Taking into account the aforementioned features of the heating, general algorithm for calculating the temperature and humidity of a paper web for such drying part design should be as follows:

a) Obtaining data on the parameters of the paper web at the entrance to the dryer part.

b) Calculation of the heat transfer value between the drying cylinder and the paper web contact layer during the contact.

c) Calculation of the heat transfer value on the thickness of the paper web during the contact.

d) Calculation of the mass transfer rate on the surface of the paper web during the contact time.

e) Calculation of the mass transfer rate for the thickness of the paper web during the contact.

f) Calculation of the heat transfer value between the environment and the contact paper web layer on the free movement area.

g) Calculation of the heat transfer value on the thickness of the paper web on the free motion section.

h) Calculation of the mass transfer rate on the surface of the paper web on the free motion section.

i) Calculation of the mass transfer rate for the paper web thickness on the free movement area.

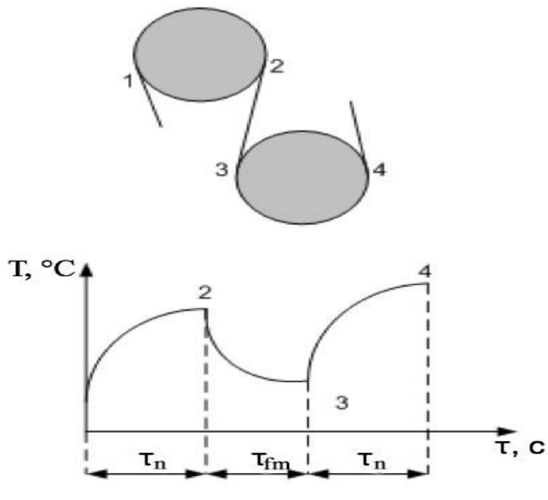

Figure-1. Control points scheme of the paper web contact with a drying cylinder and sections of free move.

The temperature of the paper at the first stage of drying is not yet high enough and therefore the mass transfer rate can be neglected. Then the calculation algorithm for the heating process will consist only of the following components:

VOL. 15, NO. 5, MARCH 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

a) Obtaining data on the paper web parameters at the entrance to the dryer part.

b) Calculation of the heat transfer value between the drying cylinder and the paper web contact layer during the contact.

c) Calculation of the heat transfer value on the thickness of the paper web during the contact.

d) Calculation of the heat transfer value between the environment and the contact paper web layer on the free movement area.

e) Calculation of the heat transfer value on the thickness of the paper web on the free motion section.

CALCULATION OF THE HEAT TRANSFER VALUE BETWEEN THE DRYING CYLINDER AND THE CONTACT LAYER OF THE PAPER WEB DURING THE CONTACT TIME

Let's record the equation of thermal balance and heat exchange during the paper web staying on a drying cylinder (unit area) [14]:

$$dq_{ct} = \alpha_{ct}(t_c - t_p)d\tau = (c_{dp} + c_w u_0)P_{dp}dt_c,$$

where t_c, t_p - temperature of the drying cylinder and paper, °C; α_{ct} - coefficient of contact heat transfer, wt / (m^2K); τ - duration of contact of a paper web with a drying cylinder, c; P_{dp} - mass of square meter of dry paper, g / m2; c_{dp} - heat capacity of a dry paper, kJ / (kgK); c_w - heat capacity of water, kJ / kgK; u_0 is the initial moisture content in a paper web, kg / kg.

After transformation we get:

$$\frac{\mathrm{dt_p}}{(\mathrm{t_c} - \mathrm{t_p})} = \frac{\alpha_{\mathrm{ct}}}{(\mathrm{c_{dp}} + \mathrm{c_w u_0})\mathrm{P_{dp}}}\mathrm{d\tau}.$$

Let us integrate the last equation by the value of t_p and obtain:

$$\frac{t_c - t_{p2}}{t_c - t_{p1}} = e^{\frac{\alpha_{ct}\tau_c}{(c_{dp}+c_w+u_0)P_{dp}}}, \quad (1)$$

where t_{p1}, t_{p2} is the temperature of the paper at the beginning and end of the drying cylinder, ° C.

From expression (1) we can find the temperature of the paper at the exit from the drying cylinder

$$t_{p2} = t_c - \frac{t_c - t_{p1}}{e^{\frac{\alpha_{ct}\tau_c}{(c_{dp}+c_w+u_0)P_{dp}}}}. \quad (2)$$

This equation is sufficient if there is a drying of a material of a small thickness. The temperature gradient for the thickness of the paper [3] is not present in this case.

The temperature will be the same across the entire paper section. This is due to the fact that the temperature of the web at the output from the press part is uniform, and the temperature at the width of the drying cylinder is the same.

In the case of massive material, the resulting equation, with small transformations, can be used solely to calculate the temperature of the contact layer of the paper.

$$t_{cl} = t_c - \frac{t_c - t_{cl0}}{e^{\frac{\alpha_{cl}\tau_c}{(c_{dp}+c_w u_{cl0})P_{dp}}}} \quad (3)$$

where t_{cl} - temperature of the contact layer of the paper, ° C; t_{cl0} - temperature of the paper at the beginning of the drying cylinder, ° C.

CALCULATION OF THE VALUE OF HEAT TRANSFER ON THE THICKNESS OF THE PAPER WEB DURING CONTACT TIME

In the process of the web heating on drying cylinders, firstly the temperature of the boundary layer increases. The middle part of the web gets warm slower. For an effective drying process, it is necessary for paper to reach a "working" temperature value throughout its thickness after the heating stage. In connection with this, for thick types of paper there is a need to calculate the temperature of the middle layer. Therefore, for calculations it is necessary to deduce another equation. The basis will be the equation of non-stationary heat conductivity [16]:

$$\frac{\partial t}{\partial \tau} = a\frac{\partial^2 t}{\partial x^2} + \frac{\varepsilon r}{(c_c + c_w u)}\frac{\partial u}{\partial \tau} \quad (4)$$

where t - temperature, ° C; τ - process duration, c; x - coordinate; a - temperature conductivity of the material, m 2 / h; ε - coefficient of phase transformation; u - moisture content, kg / kg; c_c - heat capacity of dry material, kJ / (kg ° C); c_w - heat capacity of water, kJ / (kg ° C).

In the right side of the equation there are two components (two terms). The first reflects the transfer of heat through heat conduction, and secondly, the transfer of heat through steam.

From the experimental data obtained by A. A. Lukov [3], the distribution of the temperature inside the material over the thickness has the form of a parabola with a peak (minimum temperature) in the middle layer of the material. In this case, the equivalence of the equation (4) is replaced by:

$y = -ax^2 + b$,

where y is the temperature of the paper web, ° C; x - coordinate on the thickness of the material, m; a, b - parabola coefficients.

Based on the appearance of the parabola, in future calculations we will calculate the temperature of the middle layer of paper.

Under the boundary conditions, the coefficients a and b will accept the following values:

$x = 0$; $b = t_c$,
$x = \mathrm{R}$;
$$b = \frac{(t_{cl} - t_c)}{R^2},$$

where R is the half-thickness of the material, t_c, t_{cl} - the temperature of the drying cylinder and the contact layer of the paper web, ° C.

If we substitute these values in equation (3), we obtain the temperature in the cross section of the material:

$$t = \frac{(t_{cl} - t_{ml})x^2}{R^2} + t_c.$$

where t_{ml} is the temperature of the middle layer of the paper web, ° C.

This equation is differentiated twice by dx, then we substitute the result in (4) and perform the operations similar to (1). As a result of these actions we obtain a formula for calculating the temperature of the middle layer of paper at the exit from the free movement area:

$$t_{ml} = t_{cl} - \frac{1}{2a}\left(\frac{\alpha(t_{ml0} - t_{cl})}{c_c R^2} + \right. \tag{5}$$

The greatest difficulty in calculating this formula is the definition of the coefficient ε. Its value is obtained only empirically and reflects the proportion of heat flowing through the vapor. Only the flow of heat received by the steam is accepted into the calculation.

In the general case, the coefficient ε is proposed to be calculated according to the formula given in [17]. But this method is quite complicated and requires significant additional calculations.

There is another approach to determining this coefficient [8]. It is chosen the same over the entire thickness of the paper web and it depends on the type of paper (thickness) and the temperature that the cylinder heats. Its value can be obtained by selecting the appropriate point on the graph. The graph for determining the coefficient ε was obtained from experimental data and presented in paper [17].

CALCULATION OF THE VALUE OF HEAT TRANSFER BETWEEN THE ENVIRONMENT AND THE CONTACT LAYER OF A PAPER WEB ON THE FREE MOVEMENT AREA

For a free movement area, it is necessary to make an additional mathematical model of heat exchange between the environment and the boundary layer of paper. The transfer of heat inside the material can be calculated by the formula (5) when the temperature of the drying cylinder is replaced by the ambient temperature.

In the areas of free movement, the paper web cools and moisture evaporates. This process occurs under the influence of the difference of partial pressures. The partial vapor pressure is set on the surface of the evaporation, which corresponds to the temperature of the saturated state.

The equation of thermal balance in case of evaporation of moisture from the surface of the web of paper on the free path due to the accumulated heat on the cylinder will be written as follows:

$$\beta_p(p_p - p_{en})r\, d\tau = P_{dp}(c_{dp} + c_w u_0)\, dt_{cl}, \tag{6}$$

where p_p, p_{en} - partial pressure of water vapor on the surface and in the environment, Pa; P_{dp} - weight of one square meter of paper web, kg / м2; c_{dp} - heat capacity of a dry paper web, kJ / (kgK); c_w - heat capacity of water, kJ / kgK; u_0 - initial moisture content in a paper weave, kg / kg; β_p - mass transfer coefficient, assigned to the difference of partial pressures, kg / (m2 * h * Pa); τ - the length of stay of the paper web on the free movement area, c; t_{cl} - temperature of the contact layer of the paper web, ° C.

The left side of the equation expresses the amount of heat transmitted by the paper web to the ambient air due to the evaporation of moisture. The right side of the equation corresponds to a decrease in the enthalpy of a moist material.

Equation (6) can not be integrated because the left side contains partial pressures, and in the right there is temperature. In this regard, the vise must be replaced by the temperature.

For different intervals of the temperature of the paper web, the type of replacement will be different. The basis of the replacement is the law of Charles (the second law of Gay-Lussac) [18].

Let us first consider the temperature range from 0 to 60 ° C.

The replacement will look like [18]:

$$\frac{\mathrm{p}_p}{\mathrm{p}_{en}} = \frac{t_p}{t_{en}},$$

In this case, we have a proportional relation between the partial pressures and temperatures.

Proceeding from the fact that at atmospheric pressure the pressure of the saturated pair p_{en} = 1 atm and its temperature t_{en} = 100 ° C, then the partial pressure of the water vapor at the surface of the evaporation will have the form [18]:

$$\mathrm{p_p} = \mathrm{p_{en}}\frac{\mathrm{t_p}}{100} = 1\frac{\mathrm{t_p}}{100} = \upsilon.$$

Rewrite the equation (6) in the following form:

$$\beta_p(\upsilon - a)r\, d\tau = P_{dp}(c_{dp} + c_w u)\, d\upsilon. \tag{7}$$

where a is the partial pressure of vapors in the ambient air. If we integrate the equation (7), then the pressure can be expressed as follows:

$$\mathrm{p}_p = \frac{\mathrm{p}_{en} + (\mathrm{p}_{p0} - \mathrm{p}_{en0})}{\mathrm{e}^{\frac{\beta_p r \tau_{en}}{P_{dp}(c_{dp} + c_w u)}}}. \tag{8}$$

As indicated above, this equation is valid for the temperature range from 0 to 60 ° C.

Consider the temperature range from 60 ° C to 80 ° C.

The dependence of pressure and temperature here will have another form - quadratic (a = b^2). In this regard, the replacement will look like this:

$$\frac{p_p}{p_{en}} = \left(\frac{t_p}{t_{en}}\right)^2$$

Hence, the equation (6) will have the form:

$$\beta_p(\upsilon^2 - a^2) r\, d\tau = P_{dp}\left(c_{dp} + c_w u\right) d\upsilon.$$

After integrating we obtain:

$$\frac{\left(\sqrt{p_p}-\sqrt{p_{en}}\right)\left(\sqrt{p_{po}}+\sqrt{p_{en}}\right)}{\left(\sqrt{p_{en}}+\sqrt{p_{en}}\right)\left(\sqrt{p_{po}}-\sqrt{p_{en}}\right)} = 4ae^{e^{\frac{\beta_p r \tau_{fm}}{P_{dp}\left(c_{dp}+c_w u\right)}}}. \tag{9}$$

From this equation you can get $p_п$.

For a range from 80 ° C to 100 ° C, the dependence between pressure and temperature is described by the ratio of the third degree:

$$\frac{p_p}{p_{en}} = \left(\frac{t_p}{t_{en}}\right)^3$$

Following the identical transformations described above, we obtain the following formula (10):

$$\frac{1}{6p_{en}{}^{0,67}}\Bigg(\ln\frac{\left(p_{en}{}^{0,33} - p_p{}^{0,33}\right)^2}{p_{en}{}^{0,67} + p_{en}{}^{0,33}p_{p1}{}^{0,33} + p_{p1}{}^{0,67}} + \frac{1}{p_{en}{}^{0,67}\sqrt{3}}\operatorname{arctg}\frac{2p_p{}^{0,33} + p_{en}{}^{0,33}}{p_{en}^{0,33}\sqrt{3}} +$$
$$+\ln\frac{\left(p_{en}{}^{0,33} - p_p{}^{0,33}\right)^2}{p_{en}{}^{0,67} + p_{en}{}^{0,33}p_{p1}{}^{0,33} + p_{p1}{}^{0,67}} + \frac{1}{p_{en}{}^{0,67}\sqrt{3}}\operatorname{arctg}\frac{2p_p{}^{0,33} + p_{en}{}^{0,33}}{p_{en}^{0,33}\sqrt{3}} -$$
$$-\ln\frac{\left(p_{en}{}^{0,33} - p_{po}{}^{0,33}\right)^2}{p_{en}{}^{0,67} + p_{en}{}^{0,33}p_{po}{}^{0,33} + p_{po}{}^{0,67}} + \frac{1}{p_{en}{}^{0,67}\sqrt{3}}\operatorname{arctg}\frac{2p_{po}{}^{0,33} + p_{en}{}^{0,33}}{p_{en}{}^{0,33}\sqrt{3}}\Bigg) = \frac{\beta_p r\, \tau_{fm}}{P_{dp}\left(c_{dp} + c_w u\right)}. \tag{10}$$

From this equation by the iteration method, one can determine the vapor pressure on the surface of the evaporation.

After obtaining the numerical value of the vapor pressure on the surface of the evaporation, it is possible to use the table [20] to find the temperature of the paper web at the end of the free path.

This method is suitable for individual calculations of temperatures. But when it comes to the creation of a system of automatic control, it is advisable to formulate on the basis of tabular data, the relationship between pressure and temperature.

The functional dependence, which most closely matches the table data [19], can be written as follows:

$$t_{cl} = 21.844 \ln(p_p) - 2.564 \tag{11}$$

Thus, to calculate the temperature at the end of the free moving area, it is necessary to determine the pressure (according to the corresponding formula) and substitute the obtained value in formula (3). So, in order to calculate the temperature at the end of the free moving area for a range of initial temperatures of 0 - 60 ° C, it is necessary to substitute the expression (8) instead of pn in equation (11). As a result, we obtain:

$$t_{cl} = 21.488 \frac{p_{en} + (p_{po} - p_{eno})}{e^{\frac{\beta_p r \tau_{fm}}{P_{dp}(c_{dp}+c_w u)}}} - 2.564. \tag{12}$$

A GENERAL MATHEMATICAL MODEL OF THE THERMAL MODE OF HEATING A PAPER WEB

This model will consist of two parts:

a) mathematical model of contact heat transfer;

b) mathematical model of convective heat transfer.

We will write the equation for the first drying cylinder and the free movement area. For all other sections of the equation will be similar.

First, let's write the general view of the first component.

To obtain a general equation for calculating the temperature of the middle layer at the exit from the drying cylinder, it is necessary to put the expression (3) in equation (5) instead of t_{cl} (temperature of the contact layer):

$$t_{ml} = \left(t_c - \frac{\frac{t_c - t_{clo}}{\alpha_{ct}}}{e^{\left(c_{dp}+c_w u_{cl}\right)P_{dp}}}\right) - \frac{1}{2a}\left(\frac{\alpha\left(t_{ml} - \left(t_c - \frac{\frac{t_c - t_{clo}}{\alpha_{ct}}}{e^{\left(c_{dp}+c_w u_{cl}\right)P_{dp}}}\right)\right)}{c_{dp}R^2} + \frac{a_m \varepsilon r(u_{ml} - u_{cl})}{(c_{dp} + c_w u)}\right); \tag{13}$$

VOL. 15, NO. 5, MARCH 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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Thus, to calculate the values of heat transfer in the first cylinder, we received all the necessary data. The paper on the cylinder comes with known values of the initial temperature and moisture content. The temperature of the drying cylinder is known. Predetermined: coefficient of contact heat exchange, duration of paper holding on a cylinder, mass of square meter of dry web, heat capacity of dry web, water heat capacity, mass transfer coefficient, attributed to the difference of partial pressures, factor B, known partial pressures on the material surface and in the environment.

For a site of convective drying, similar equations can be obtained as follows:

a) In accordance with the temperature of the paper at the exit from the drying cylinder one of the formulas (8,9,10) is selected;

b) The value obtained for the chosen formula will be substituted in (11);

c) The temperature of the middle layer of a paper web on the free path is calculated by the formula (5) taking into account the value obtained by the formula (11) and has the following form:

$$t_{cl} = (21.488p_p - 2.564) - \frac{1}{2a}\left(\frac{\alpha\left(t_c - (21.488p_p - 2.564)\right)}{c_{dp}R^2} + \frac{a_m \varepsilon r(u_{ml} - u_{cl})}{(c_{dp} + c_w u_{ml})}\right); \qquad (14)$$

RESULTS

To verify the adequacy of the developed mathematical model were used experimental data during the operation of the paper-making machine in the normal operation mode.

As the output parameters for the measurement, the temperature of the paper at the exit from each drying cylinder and at the end of the free motion sections was selected:

$T_p = [T_{1,p}, T_{2,p} \ldots T_{k,p}]$,
where T_p - an array of temperatures of a paper web on the exit from the drying cylinder; k - number of drying cylinders in the area of heating the paper web;
$T_{fm} = [T_{1,fm}, T_{2,fm} \ldots T_{k,fm}]$,
where T_{fm} - an array of temperatures of a paper web at the end of the free movement area.

The object configuration for conducting experimental studies was as follows:

- 8 sections of free movement;
- drying cylinders arranged in chess order.

Experimental data were obtained by contactless method using modern pyrometers and possibly-permissible error that does not exceed 1%. The results of experimental studies and data calculated with the help of a mathematical model are depicted in the graphs of changes in the temperature of the paper web in time.

Similar data was obtained for the remaining drying cylinders and free movement areas. For this study, it is advisable to use statistical criteria as a criterion for the adequacy of the results of mathematical modeling for experimental data. The application of these criteria allows us to establish quantitative limits of adequacy. In this way we can more objectively determine degree of identity of the object and its model.

The first method involves testing the hypothesis of the proximity of the mathematical expectations of each k-th component of the model and the real system. It is as follows. Conduct Ns experiments on a real object and receive for each k component of the sample of values of the system. Then perform Nm experiments on the model and receive the same k-th component of the sample of sample model values.

Usually trying to make the volumes of the samples identical (Ns = Nm), but in-person experiments are very expensive, so, usually, $N_m > N_s$.

After these stages, calculate the Student's criterion and compare it with the tabular value. It is necessary to set the level of significance a and according to the table of a two-sided critical area of Student's criterion determine its critical value t_{kr}. In the case when the condition $t_k < t_{kr}$ is fulfilled, the hypothesis about the proximity of mathematical expectations for the k-th component of the model and the system is adopted.

The second method involves checking the hypothesis of the homogeneity of the two dispersions S_k^(2, s) and S_k^(2, m) for each k-th component. The parameter S_k^(2, m) is the variance of the model feedback with respect to the mean value of the system response.

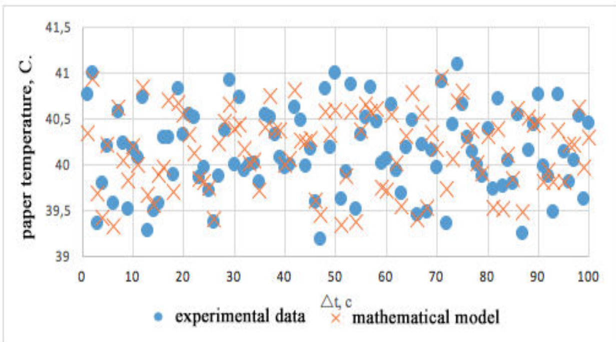

Figure-2. Temperature of the paper at the outlet of the first drying cylinder.

VOL. 15, NO. 5, MARCH 2020 ISSN 1819-6608
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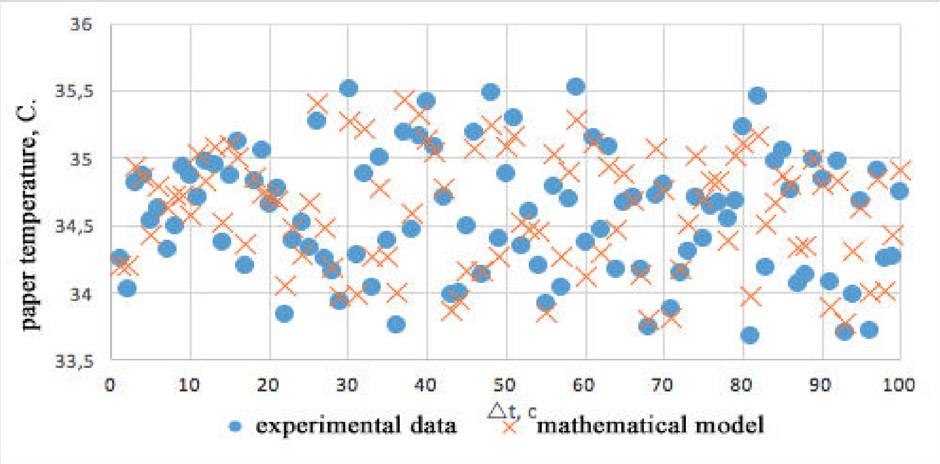

Figure-3. Temperature of the paper at the exit from the 1st area of free movement.

This hypothesis is accepted in the case when the condition $F < F_{kr}$ is fulfilled, where F and F_{kr} are the calculated and critical values of Fisher's criterion.

After calculating the selective value of Fisher's criterion, the table defines the critical value of this criterion, Fkr, using the information on the degree of freedom more, less than the level of significance.

Estimates of statistical characteristics for the data obtained during the experiment are shown in Table-1.

Table-1. Statistical characteristics of experimental data.

Experiment number	Statistical characteristics of the system	
	Mathematical expectation	Dispersion
First drying cylinder	40.14	0.21
First free movement area	34.58	0.21
Second drying cylinder	47.67	0.14
Second free movement area	41.86	0.15
Third drying cylinder	56.2	0.15
Third free movement area	50.7	0.15
4-th drying cylinder	65.57	0.17
4-th free movement area	54.83	0.12
5-th drying cylinder	74.6	0.26
5-th free movement area	62.8	0.19
6-th drying cylinder	84.08	0.18
6-th free movement area	65.66	0.13
7-th drying cylinder	90.3	0.33
7-th free movement area	70.61	0.21
8-th drying cylinder	96.51	0.41
8-th free movement area	75.62	0.25

The data for the results of mathematical modeling was obtained similarly (Table-2):

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Table-2. Statistical characteristics of data obtained by model.

Experiment number	Statistical characteristics of the model	
	Mathematical expectation	Dispersion
First drying cylinder	40.14	0.18
First free movement area	34.41	0.18
Second drying cylinder	47.68	0.14
Second free movement area	42.2	0.14
Third drying cylinder	56.2	0.15
Third free movement area	50.68	0.14
4-th drying cylinder	65.61	0.15
4-th free movement area	54.8	0.12
5-th drying cylinder	74.58	0.23
5-th free movement area	62.8	0.17
6-th drying cylinder	84.1	0.17
6-th free movement area	65.65	0.11
7-th drying cylinder	90.24	0.3
7-th free movement area	70.63	0.19
8-th drying cylinder	96.54	0.36
8-th free movement area	75.62	0.22

Using the data from Figure-1 and Figure-2, in the Figure-3 the calculated and tabular values of the Student's and Fisher's criteria are shown, they were also used for testing the mathematical model for adequacy (Table-3).

Table-3. Calculated and tabular values of Student's and Fisher's criteria.

Experiment number	Student's criteria		Fisher's criteria	
	Calculated	Tabular	Calculated	Tabular
First drying cylinder	0.73	1.984	1.13	1.26
First free movement area	0.11		1.17	
Second drying cylinder	0.45		1.02	
Second free movement area	0.3		1.07	
Third drying cylinder	0.87		1.06	
Third free movement area	0.52		1.07	
4-th drying cylinder	0.06		1.19	
4-th free movement area	0.07		1.03	
5-th drying cylinder	0.44		1.16	
5-th free movement area	0.93		1.11	
6-th drying cylinder	0.19		1.1	
6-th free movement area	0.62		1.17	
7-th drying cylinder	0.04		1.15	
7-th free movement area	0.36		1.17	
8-th drying cylinder	0.29		1.13	

By comparing the calculated value of the Student and Fisher criteria with tabular data (for all points of the arcs T_p and T_{fm}), we can conclude that there is no reason to reject the hypothesis that the mathematical model of the paper web heating is adequate. Therefore, we will assume that the mathematical model adequately describes the technological process of heating the paper web in the drying section of the paper-making machine.

CONCLUSIONS

According to the results of the analysis of existing decisions and researches, the main features of the mathematical modeling of the first stage of drying of a paper web in a paper-making machine were determined. These features can be formulated as follows:

a) Due to the low initial temperature of the paper web, in the beginning of drying, there is practically no mass transfer of moisture in the material. In this regard, this component can be neglected.

b) Based on the features of the drying configuration, the mathematical model should consist of models of the contact (during the stay of the paper web on the drying cylinder), and of the convective (in the area of free movement between the cylinders) heat exchange.

c) The non-stationary heat transfer processes in free movement areas are established and its dependence on temperature at its beginning is determined.

d) The equation for calculating the temperature of the central layer of the paper web at the exit from the drying cylinders and at the end of the free motion sections at the first stage of drying of the paper web (at the stage of its heating) is derived.

e) A validation of the adequacy of the mathematical model obtained by real experimental data has been performed.

f) One of the most promising areas for further use of the developed solution is for Failure Mode and Effect Analysis (FMEA) using the Ontology-enabled Process described in the work [20-24].The second perspective direction of using the developed mathematical model is the creation on its basis of the simulation model of drying technological process in order to synthesize and verify [25-28] the effectiveness of the control systems.

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