A C T A A L I M E N T A R I A P O L O N I C A
Vol. VII (XXXI), No. 3-4 1981

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WOOD DESTRUCTION RATE VERSUS COMBUSTION CONDITIONS IN THE PROCESS OF GENERATING WOOD SMOKE — A MATHEMATICAL APPROACH

Key words: wood combustion, generating of wood smoke, process optimization.

The effect of air flow rates on the temperature and rate of wood combustion was studied. The results obtained have been used to establish functional relationships between the air flow rate and combustion temperature, as well as the air flow rate and combustion rate. These functions may be helpful in optimizing the process of generating wood smoke.

INTRODUCTION

After it has been started, the process of wood combustion which results in the production of wood smoke, has a spontaneous character. Two basic stages may be distinguished herein [5]:

— thermal decomposition of wood,

— oxidation of the volatile decomposition products.

According to the results obtained by Kuriyama [4], during the thermal decomposition of wood with the growth of temperature, we first encounter the process of drying (50-100°C) which is followed by the decomposition of wood (100-500°C). The volatile products of thermal decomposition have a high vapor pressure and, consequently, form a sheath around the glowing wood which causes that the composition, in principle, has an anaerobic character. The outer layer of the sheath gets in contact with atmospheric oxygen and forms the so-called oxidation zone. Here the volatile products of wood decomposition undergo oxidation which is a strongly exothermic process. Because of the constant elementary composition of which does not depend on its type [3] the amount of heat liberated during oxidation of the wood decomposition products is constant and amounts to 1.99×10^6 J/kg [5]. This large amount of heat released, in combination with the low specific heat of the gases produced, makes the temperature in the oxidation zone to reach a high level, and this in turn affects the decomposition rate of wood.

As it is known [6] both the temperature of the oxidation zone and the rate of reactions taking place in it depend mostly on the intensity of the penetration of air (oxygen) into this zone. This fact creates the possibility of influencing the rate of the spontaneous process of wood thermodestruction by means of regulating the air flow through the combustion zone. A prerequisite for an effective action in this respect is the knowledge of functional relationships linking the wood destruction rate with the combustion temperature and the air flow rate through the combustion zone. This relationship is given in literature [1, 8] in the form of a linear equation which allows for the possibility of a thermal decomposition of wood also in temperatures in which this decomposition does not take place. Therefore, said equation should be treated only as an approximated description of the relationship discussed. A search for a more general description of this relationship seemed thus to be an actual task and constituted the purpose of the present study.

EXPERIMENTAL

The research material was constituted by sawdust of grey alder (*Alnus incana*) with an average granulation of 0.48 mm. It was conditioned by wetting so as to achieve moisture content of ca 20%, 40% and 60%, respectively. The actual moisture content was determined by the oven method.

The combustion of sawdust was carried out in a laboratory size smoke generator designed at the Polish Meat and Fat Research Institute [1, 2]. A diagram of the generator is shown in Fig. 1. With the combustion of sawdust, the heat zone moved from top to bottom, current-wise to the air and smoke direction. The elements of the system which were in direct contact with smoke were made of glass and all the joints were ground which guaranteed complete tightness to the system and easy dismantling for collection of the condensate. Sawdust was poured into the combustion chamber to a height of 400 $\pm$ 25 mm where it was delicately and uniformly packed. After testing the tightness of all joints, starting the freezer and allowing water to flow through the condenser, the vacuum pump was switched on. The air flow rate was pre-set for each test (2000, 1600, 1000 and 400 l/h). Next the upper sawdust layer was ignited. An analogue record of temperature of the combustion zone was conducted during each combustion process using thermo-couples PtRh30 (PtRh6 *).

Each test was made in two parallel repetitions. The amount of combusted sawdust was determined on the basis of the difference in sawdust weight before and after combustion.

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*) The thermo-couples were made and calibrated in the Institute of Fine Mechanics.

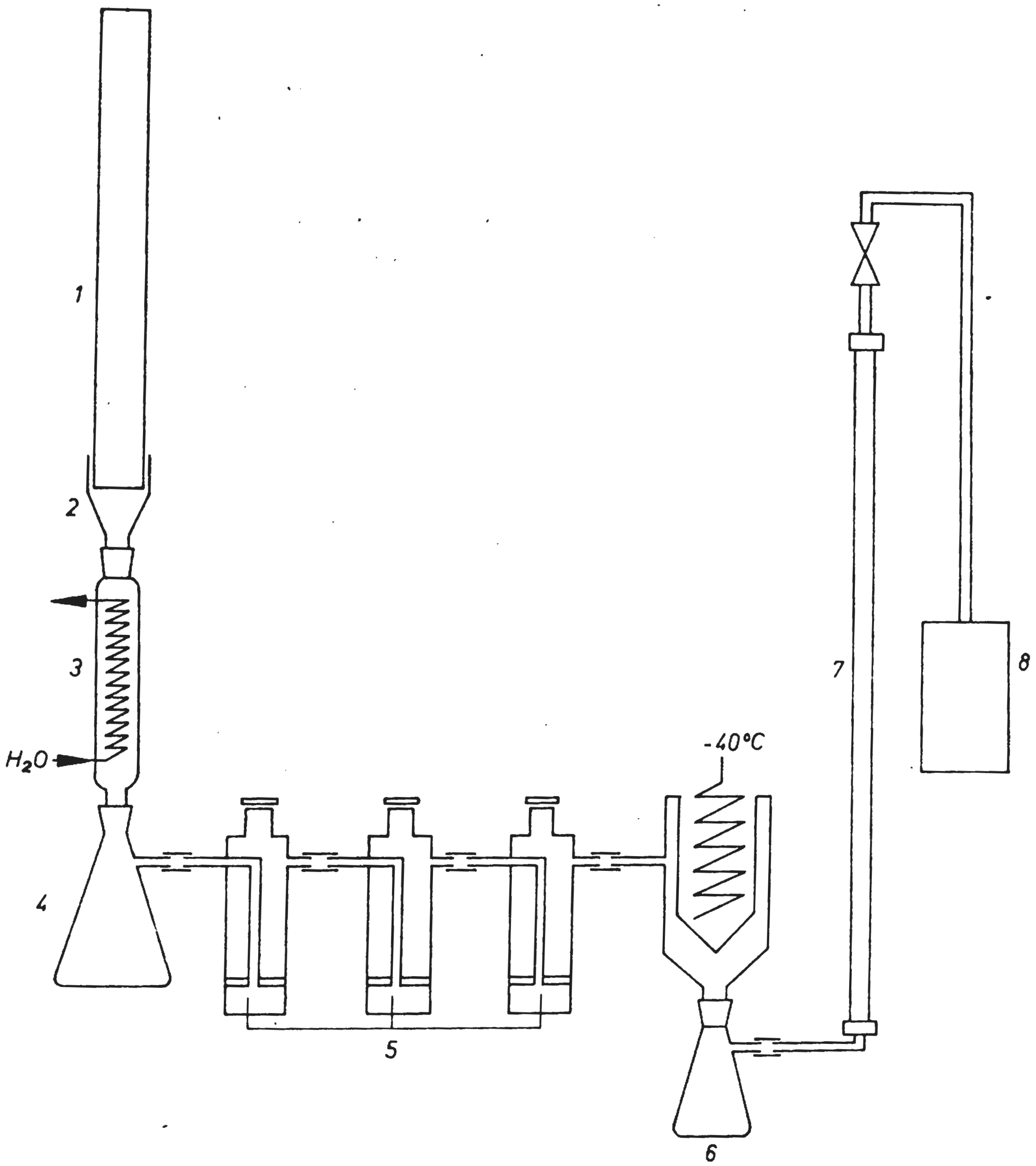

Fig. 1. Equipment for combustion of sawdust; 1 — combustion chamber (quartz), 2 — fritted Buchner funnel, 3 — water cooled condenser, 4 — condensate collecting flask, 5 — gas washing bottles (with sintered tips), 6 — cold trap, 7 — rotameter, 8 — pump

The values of the linear air flow rate, recorded temperatures of the heat zone, combustion time, amount of sawdust subject to combustion and experimental combustion rates (in terms of dry sawdust substance) are presented in Table 1.

DISCUSSION

1. EFFECT OF THE AIR FLOW RATE ON THE TEMPERATURE OF THE COMBUSTION ZONE

The analysis of the values of the combustion temperature included in Table 1 suggests that there is a non-linear dependence of this variable on the air flow rate. This conclusion conforms with an earlier report [1].

T a b l e 1. Conditions of wood combustion

Series	1				2				3			
Moisture contents	19.24				47.54				59.97			
U (cm/min)	*T* (°C)	*m* (g)	*t* (min)	*v* (g/min)	*T* (°C)	*m* (g)	*t* (min)	*v* (g/min)	*T* (°C)	*m* (g)	*t* (min)	*v* (g/min)
2653	1185	114	6	15.34	1074	157	7	11.77	1025	201	7	11.49
2653	1177	112	6	15.08	1099	152	6.5	12.27	980	200	6.5	12.32
2122	1172	115	8.5	10.93	1071	160	10	8.39	945	222	10	8.89
2122	1209	115	8.5	10.93	1098	162	10	8.50	934	232	10	9.29
1326	1070	115	17	5.46	1007	167	16.5	5.31	791	195	16.5	4.73
1326	1090	115	17	5.46	1029	157	15	5.49	876	184	15	4.91
531	1030	115	41.5	2.24	931	154	41.5	1.95	830	184	41.5	1.77
531	992	115	41	2.27	923	140	36	2.04	837	190	36	2.11

However, according to the later study temperature is a function of two variables (wood combustion rate and air flow rate) which makes it very difficult to control the combustion temperature. For this reason, the author of the present study has tried to express this temperature as a function of one variable only, i.e. of the rate at which air flows through the combustion zone.

The starting point was constituted by the known relation:

$$\Delta Q = m \cdot c \cdot \Delta T \tag{1}$$

where:
ΔQ heat increment
m — mass of wood
c — specific heat of wood
ΔT — temperature increment

It can be assumed that the mass of combustion gases in the zone surrounding the decomposing particles of wood is practically equal to the mass of volatile products resulting from the decomposition of wood. Taking into account the radical-chain mechanism of reactions occuring in the oxidation zone, the share of oxygen in these reactions and the possibility of interrupting the chains of reaction, the following equation has been worked out:

$$\frac{dm}{du} = q \cdot m \cdot (u - u_m) \tag{2}$$

where:
q — proportionality constant
u — rate of air flow through the combustion zone
u_m — constant characterizing the effect factors interrupting the reaction chain

Intergration of the above formula gives the following result:

$$m = m_m \cdot \exp\,[q(u - u_m)^2] \tag{3}$$

where:
m_m — is the mass of the volatile products of the decomposition of wood obtained at u = u_m

After introducing this expression to equation (1) and its appropriate transformation, the following dependence of the combustion temperature upon the air flow rate is obtained:

$$T = T_m \cdot \exp\,[\text{-}q(u - u_m)^2] \tag{4}$$

On the basis of experimental data included in Table 1 the parameters of the above equation were calculated and presented in Table 2. The latter table presents also the values of the correlation coefficients of the linear form of this equation. In all cases, these values are very high (statistical

Table 2. Values of the parameters of equation (4) and of the corresponding correlation coefficient

Series	1	2	3
Moisture contents	19.24	47.54	59.97
q	$2.3356\ 10^{-8}$	$3.6485\ 10^{-8}$	$5.1865\ 10^{-8}$
T_m	1204.5	1089.1	926.6
u_m	3312.0	2641.9	2476.6
r	0.9877	0.9975	0.9697

significance — $P < 0.001$) which indicates that the dependence proposed and illustrated by equation (4) describes well the course of the changes of the combustion temperature depending on the air flow rate. The compliance of temperatures thus calculated with the experimental values is shown in Fig. 2.

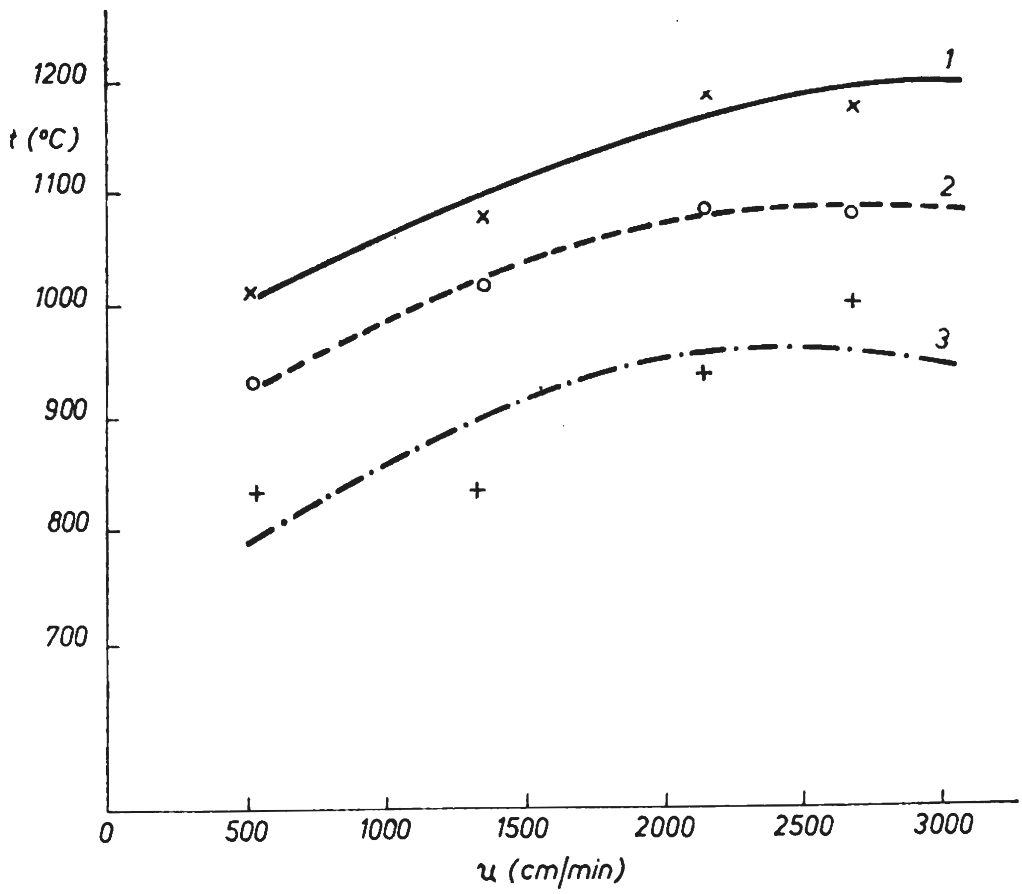

Fig. 2. Combustion temperatures versus air flow rates by various humidity of sawdust; 1 — 19.24% of water, 2 — 47.54% of water, 3 — 59.97% of water

It should be added that the character of the function presented in equation (4) determines the physical meaning of the constant "u_m" representing the influence of factors interrupting the chain of reaction. The u_m value determines the air flow speed at which a maximum value of the heat zone temperature is obtained.

Both equation (4) and the experimental results obtained make it possible to draw the conclusion that in order to control the temperature of the combustion zone it is sufficient to control the air flow rate through this zone. The value of the parameters in this equation obviously depend on the design of the furnace of the smoke generator, kind and grading of wood, and its humidity. Each of these factors may be arbitrarily chosen and after establishing the parameters of equation (4) it is possible to produce wood smoke at a postulated temperature by means of controling the air flow rate only.

2. EFFECT OF THE AIR FLOW RATE ON WOOD COMBUSTION RATE

The data presented in Table 1 show that changes in the air flow rate result in a change of the wood combustion rate. This effect has a non-linear character and the respective changes are non-monotonic. The latter issue was analysed in earlier studies [1, 8] where it was observed that the combustion rate may be well described as a linear function of the product of the air flow rate and the combustion temperature, i.e. as many as two different variables, one of which, as demonstrated above, is dependent on the other. This is not convenient in the process of controlling the wood combustion rate and, consequently, the rate of wood smoke production. In this connection, it proved useful to formulate a functional relationship with a single decision-making variable i.e. the air flow rate.

Because of the fact that the decomposition of timber is a first-order reaction [7], the time necessary for an n-fold reduction of the mass of wood encompassed by the combustion zone is as follows:

$$t = \frac{1}{k} \cdot ln\ N \tag{5}$$

where:

k — rate constant of wood decomposition

In stationary conditions the wood decomposition rate is proportional to the speed of the displacement of the combustion zone through the sawdust bed:

$$v = \alpha \cdot \frac{1}{t} = \alpha \cdot \frac{L}{Q} \tag{6}$$

where:

α — proportionality constant

l — thickness of combustion zone

t — time expressed by equation (5)

L — thickness of the sawdust bed

Q — time needed for the passage of combustion zone through the whole bed of sawdust.

The thickness of the combustion zone is proportional to the air flow rate (heat convection) and it may be assumed [2], that this relationship may be described by the following equation:

$$L = \beta \cdot u^b \qquad (7)$$

where:
β and b — constants
After introducing expressions (5) and (7) into equation (6), assuming that constant k in expression (5) fulfils the Arrhenius equation and taking into consideration equation (4) the following formula is obtained:

$$ln\ v = A + b\ \ln\ u + \frac{C}{T_m} \cdot \exp\left[q(u - u_m)^2\right] \qquad (8)$$

where:
A — integration constant

$$C = \frac{\Delta E}{R}$$

ΔE — activation energy
R — gas constant
On the basis of the results listed in Table 1 and 2, the parameters of this equation were calculated and listed in Table 3. The total correlation coefficient of the linear form of the above relationship was also given.

Table 3. Values of the parameters of equation (8) and of the corresponding correlation coefficient

Series	1	2	3
Moisture constents	19.24	47.54	59.97
A	23.0817	−16.4032	1.3445
b	−0.6262	1.7059	0.5499
C	−18463.61	5923.40	−3276.43
r	0.9978	0.9992	0.9986

The very high numerical values of the correlation coefficient (statistical significance $P < 0.001$) indicate that the relationship expressed by equation (8) describes well the wood decomposition rate as a function of the air flow rate. The compliance of the calculated combustion rate values with the experimental values is illustrated in Fig. 3. Thus, this relationship may be successfully applied to a control of the rate of wood smoke production.
As shown above, both the temperature of the combustion zone and the wood decomposition rate remain in a strict functional relationship with the rate of air flow through the combustion zone, i.e. a parameter which may be comparatively easily controlled at industrial conditions. Thus, the

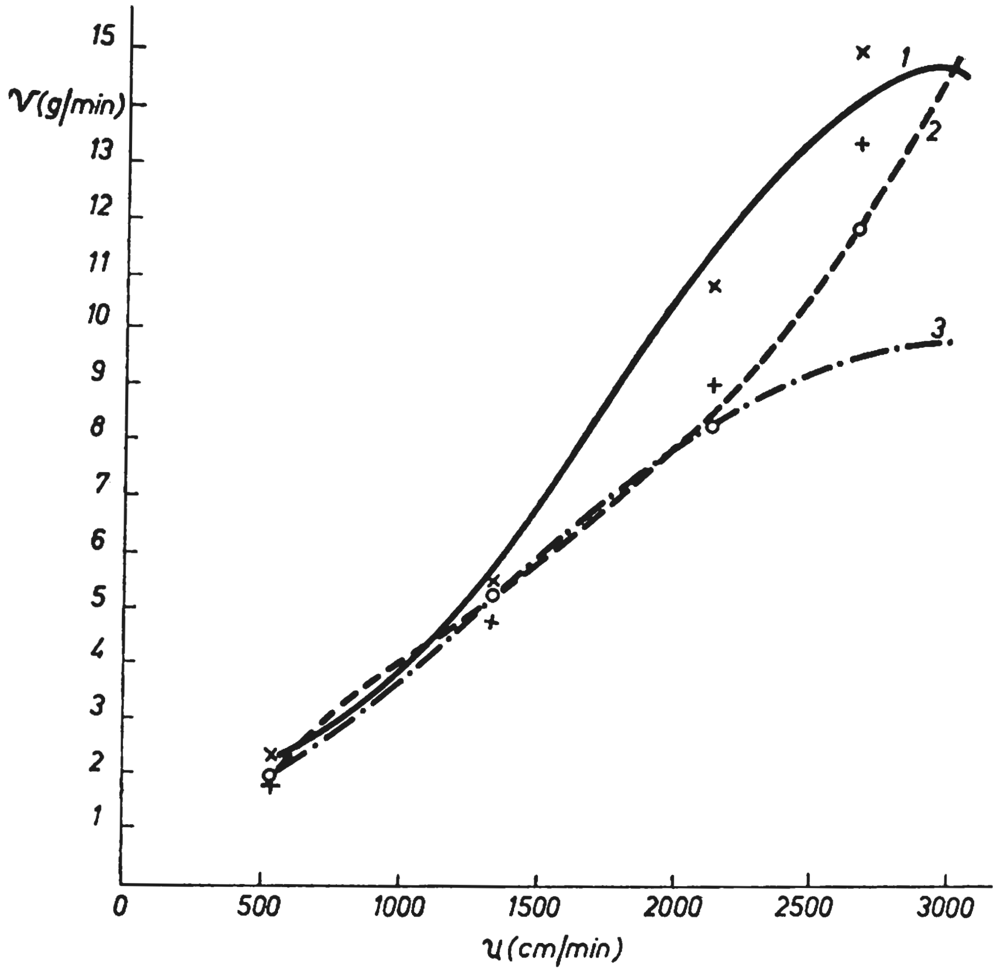

Fig. 3. Combustion rates versus air flow rates by various humidity of sawdust; 1 — 19.24% of water, 2 — 47.54% of water, 3 — 59.97% of water

relationships established create a possibility of optimizing the process of wood smoke production and of the production of smoke flavours.

CONCLUSIONS

1. The temperature of the combustion zone is linked with the rate of air flowing through it by a functional relationship representing a Gaussian curve.
2. The logarithm of the wood combustion rate is a linear function of the combustion temperature and the logarithm of the air flowing rate.
3. The observed relations may be used for the optimization of the smoke production process.

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PRÓBA FUNKCYJNEGO OPISU WPŁYWU WARUNKÓW SPALANIA DREWNA NA SZYBKOŚĆ JEGO ROZKŁADU W PROCESIE WYTWARZANIA DYMU WĘDZARNICZEGO

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S t r e s z c z e n i e

Badano wpływ szybkości przepływu powietrza na temperaturę strefy żaru i szybkości spalania drewna. Materiał badawczy stanowiły trociny olchy szarej o średnim rozdrobnieniu 0,48 mm. Spalanie trocin prowadzono w modelowej wytwornicy dymu (rys. 1). Warunki spalania zestawiono w tabeli 1.

Na podstawie uzyskanych wyników stwierdzono, że:

1. Temperatura żaru związana jest z szybkością przepływu powietrza przez strefę żaru zależnością funkcyjną przedstawiającą krzywą Gaussa. Proponowana zależność dobrze opisuje przebieg zmian temperatury strefy żaru wraz ze zmianą szybkości przepływu powietrza. Zgodność temperatur wyliczonych z wartościami doświadczalnymi przedstawiono graficznie (rys. 2).

2. Logarytm szybkości spalania drewna jest liniową funkcją temperatury żaru i logarytmu szybkości przepływu powietrza przez strefę żaru. Uzyskano dobre dopasowanie krzywych do wartości doświadczalnych (rys. 3).

Jak wykazano, zarówno temperatura strefy żaru, jak i szybkość rozkładu drewna pozostają w ścisłym związku z szybkością przepływu powietrza przez strefę żaru, tj. parametrem, który można stosunkowo łatwo regulować w warunkach przemysłowych. Zatem znalezione zależności stwarzają możliwość optymalizacji procesu wytwarzania dymu wędzarniczego, jak też produkcji preparatów wędzarniczych, gdyż jak wiadomo skład chemiczny dymu i pośrednio preparatów zależy w głównej mierze od warunków, w których drewno poddawane jest degradacji termicznej i utlenianiu.