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VERSION OF A MATHEMATICAL MODEL OF PURGE VENTILATION SYSTEM WITH A COMPLEX RECUPERATIVE HEAT EXCHANGER

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The aim of the study is to develop a design of an air-heating recuperator for a purge ventilation system of a building inbuilt for the purpose of utilizing lower-grade heat from ventilation gases and emissions with the associated production of thermoelectricity. An experimental design of an air-heating recuperator as part of an experimental purge unit has been developed. It includes a thermoelectric source of electromotive difference, which operates as a result of the associated conversion of heat into electricity, which allows utilizing lower-potential heat of ventilation releases from 40°C to 60°C.

Key words: purge unit, utilization, heat transfer coefficient, electric power, efficiency, autonomy, ventilation gases, thermoelectricity

INTRODUCTION

One of the main directions of increasing the efficiency of ventilation units is the use of devices and equipment complexes for the utilization of lower-grade heat [1], [13]. This makes possible to reduce emissions of harmful substances and lower-grade heat in order to protect the environment and improve environmental safety of the adjacent to the building territory [1] to [3]. The solution to the problem posed in this work proposes the installation of innovative designs of recuperative heat exchangers in the purge ventilation systems and mathematical modeling of heat exchange processes with the associated production of thermoelectricity in them.

In ventilation systems, recuperation is the transfer of heat from the air removed from the room to the supply air taken from the outside of the building using the supply fan.

Recuperation uses purge units with plate and rotary heat exchangers (recuperators), with and without enthalpy (moisture return), as well as ceramic recuperators (regenerators) of heat [13].

The supply and exhaust system with heat recovery is designed to obtain constant air exchange due to mechanical ventilation in private homes, offices, hotels, cafes, conference halls, other domestic and public premises, industrial buildings, as well as the recovery (return) of heat energy from the air removed from the premises to heat the supply purified air. Warm polluted air from the room enters the heat recovery unit, where it is cleaned using a filter, then the air passes through the recuperator and is removed through the air duct with the help of an exhaust fan to the outside. Clean cold air from the street enters the unit through air ducts, where it is cleaned with a supply filter, then passes through a recuperator and enters the premises using a supply fan. Saving heat energy when installing recuperators and heat exchangers varies from 60-80%.

To improve the efficiency of the systems for deep utilization of lower-grade heat in the purge ventilation systems, it is proposed to use a complex plate heat exchanger-recuperator, in the design of which semiconductor thermoelectric Peltier elements are inbuilt. They provide additional heating of the supply air, cooling the removed air with the accompanying generation of electricity, which is necessary for autonomous power supply of the purge unit and additional heating of the supply air.

The main principle of the thermoelectricity effect is the phenomenon of obtaining electrical energy directly from heat. The transition of thermal energy into electrical energy occurs in thermionic n-p converters, which is a pair of conductors made of different materials, connected at opposite ends. When one of the junctions of the element is heated more than the other, a thermoelectric effect occurs [4] to [6].

MATERIALS AND METHODS

To achieve the above goals, an experimental setup was developed and a number of experiments were carried out, on the basis of which a mathematical model was developed for controlling heat flows and optimizing the processes of the ventilation system with the calculation of the main characteristics of the thermoelectric generator.

The scheme of the experimental installation with overall dimensions and the designation of the main components is shown in Figure 1.

The investigated plate air heater-recuperator is assigned the designation RK1. Supply air temperature T1=20°C.

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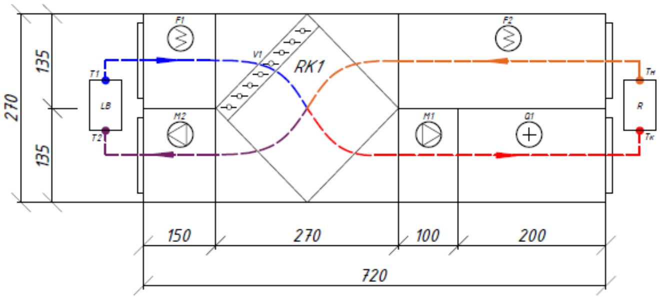

Figure 1: General view of the experimental system: RK1–investigated plate air-heating recuperator; F1–Supply filter; F2–exhaust filter; M1–Supply fan; M2–Exhaust fan; Q1–electric calorifier; T1 and T2–temperatures of the supply and exhaust air; Tк–air temperature in the heated room; Tн–temperature of the exhaust air from the room; V1–an adjustable damper.

The temperature of the supply air after heating in the recuperator Tc=27.7°C. The temperature of the removed air from the room Tn=42.8°C. The temperature of the removed air after cooling in the recuperator T2=27.7°C.

Heated air was used as a heat carrier. The working medium used was air drawn by a fan from the laboratory room. Experiments on the study of heat transfer under counterflow in the thermal power section were carried out for a number of fixed speeds and air flow at the experimental installation.

Figure 2 shows a diagram of the movement of air flows with an indication of the temperatures at the entrance and exit from the room and the ventilation system. Supply air is indicated in blue, exhaust air in blue. The orange color indicates the air being removed from the room. The purple color indicates the air being removed to the street.

The drawing and fragments of the experimental setup section are shown in Figures 2-3.

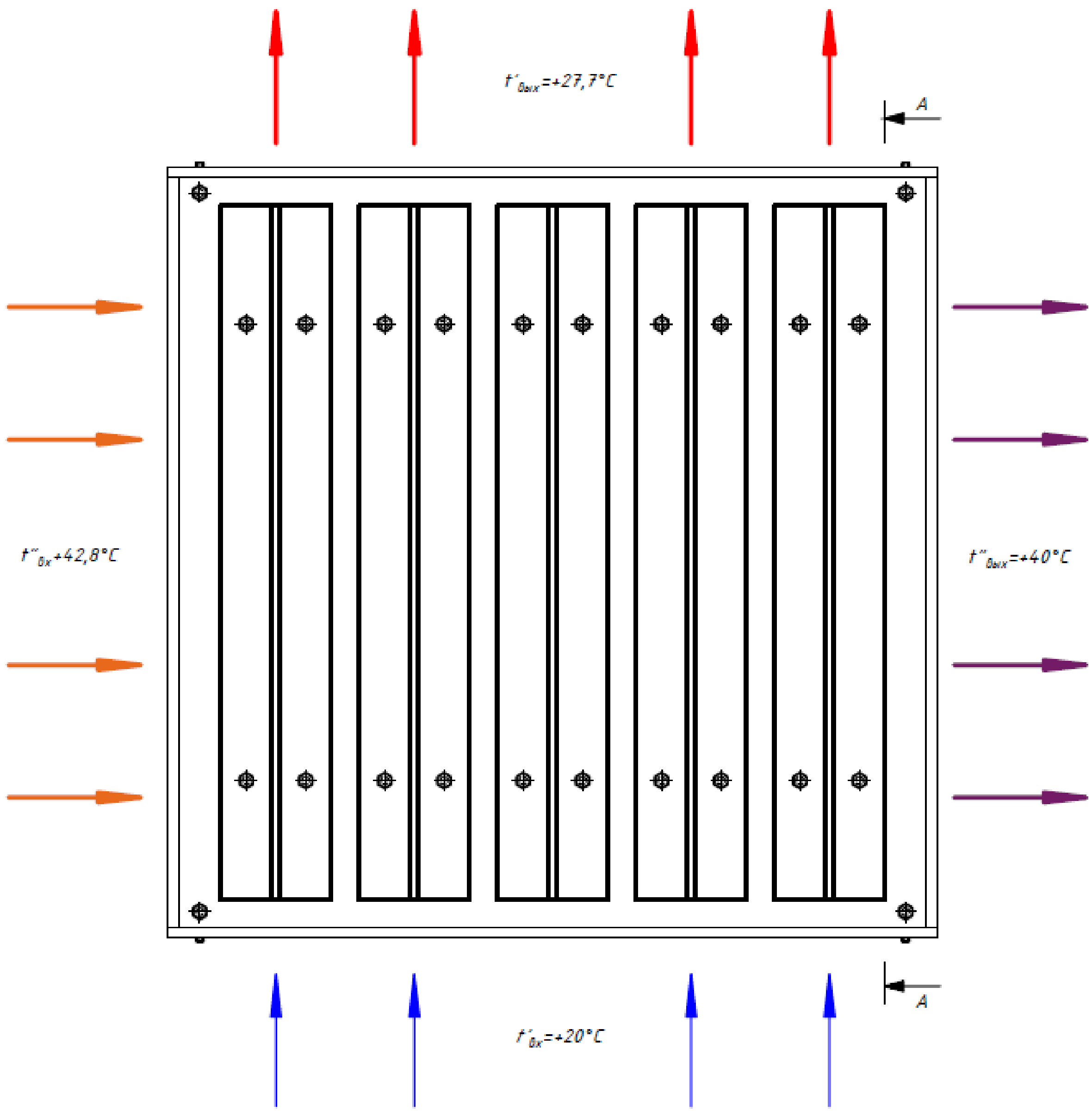

Figure 2: Diagram of the air flows movement in the investigated plate air-heating recuperator

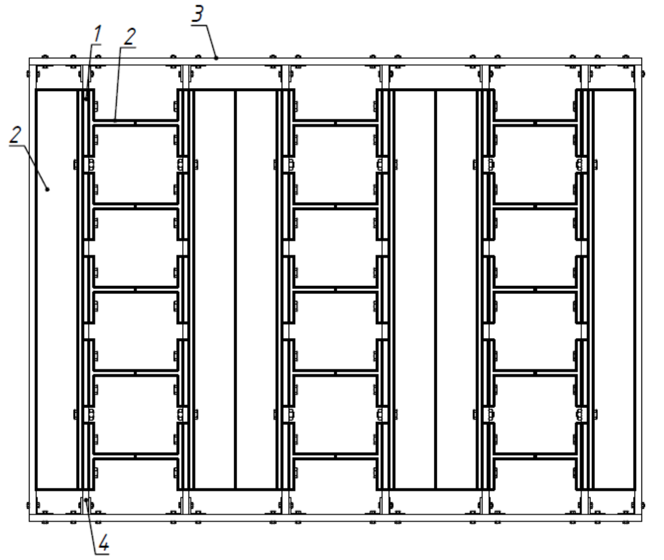

Figure 3: Section A-A of the experimental system: 1–Peltier thermoelectric element of 40x40mm format; 2–an aluminum radiator with dimensions of 40x25x3.0mm; 3–heat exchanger body; 4–walls of the heat exchanger made of 4mm thick aluminum sheets.

In accordance with the passport for Peltier semiconductor thermoelectric elements, the main technical characteristics are:

- coefficient of thermal EMF $\alpha=12.97\cdot10^{-3}$ V / K;
- Q factor$=2.8\cdot10^{-3}$ K^{-1};
- electrical conductivity coefficient $\sigma=8\cdot104$ohms$^{-1}\cdot$m^{-1};
- the coefficient of thermal conductivity of the element $\lambda=146$W/m$^{2\cdot}$°C;
- coefficient of thermal conductivity of aluminum $\lambda=221$W/m$^{2\cdot}$°C [5];
- the Peltier thermoelectric element has a format of 40x40mm;
- aluminum radiator has dimensions of 40x25x3.0mm;
- heat exchanger walls made of aluminum sheets, 4 mm thick [12].

The flow temperature was calculated as the arithmetic mean of the readings of mercury thermometers at the points of entry and exit from the channels of thermoelectric sections [7] to [8].

The average air velocity in the channels of thermoelectric sections was determined by the expression:

$$\bar{\omega}=c_H\cdot\omega_{aHeM},m/s \tag{1}$$

where c_H=0,91–coefficient of unevenness of flow.

The total heat perception of the air flow was determined from the heat balance equation:

$$Q'=\bar{\gamma}_B\cdot\bar{G}_{KaN}\cdot\left(t'_{BIX}-t'_{BX}\right)\cdot10^3 \tag{2}$$

where $\bar{\gamma}_в=c_в\cdot\rho_в$, $c_в$, $\rho_в$-heat capacity and air flow density at its average temperature, kJ/(kg°C), kg/m^3; $\bar{G}_{кан}$–duct air flow $\bar{G}_{кан}=\bar{\omega}\cdot F_{кан}$, m^3/h; $t'_{вх}$,$t'_{вых}$–air temperature at the inlet and outlet of the channel of the heat exchange element, for the passage of the heated air medium,°C;$F_{кан}$–channel cross-sectional area determined from the geometric dimensions of the channel, m.

To determine the heat transfer coefficient, the stationary heat flow method was used, which uses the Newton-Richmann law:

$$dQ'=\alpha_{F_{cm}}(t'_{B.cm}-t')dF_{cm},°C \tag{3}$$

where $t'_{в.ст}$, t'–temperatures of the heat-transfer surface and air, respectively, °C;$F_{ст}$–heat transfer surface area, m^2.

In the event that all the quantities entering into equation (3) refer to small elements of the body surface, then the average coefficient of heat transfer from the heat transfer surface was determined for each individual experiment, respectively, from the expression [9] to [10]:

$$\bar{\alpha}=\frac{\frac{1}{L}\int_0^L q(x)dx}{\frac{1}{L}\int_0^L\left(t'_{B.CT}-t'\right)sx}=\frac{Q'}{F_{CT}\times\left(\bar{t}'_{B.CT}-\bar{t}'\right)},W/(m^2\cdot°C) \tag{4}$$

where $F_{ст}$–calculated heat transfer surface of the heat exchange surface, m^2;$\bar{t}'$–the average temperature of the heated air flow in the channel, determined from the ratio, °C:

$$\bar{t}'=\frac{t'_{BX}+t'_{BIX}}{2},°C \tag{5}$$

where $\bar{t}'_{в.cm}$–the average temperature of the heat exchange surface from the side of the heated air flow, calculated by the formula (6), °C:

$$\bar{t}'_{B.cm}=\bar{t}_{cm}-\frac{Q'}{\frac{\lambda_{cm}}{\delta_{cm}}},°C \tag{6}$$

where $\delta_{ст}$–the thickness of the heat transfer surface is 2mm; $\lambda_{ст}$–coefficient of thermal conductivity of the material of the heat transfer heating surface, W/(m·°C);-the average wall temperature, calculated by the formula (7),°C:

$$\bar{t}_{cm}=\frac{\bar{t}'+\bar{t}''}{2},\ °C \tag{7}$$

where $\bar{t}''$–the average temperature of the heating air in the channel, calculated by (8) similarly to (5), °C.

$$\bar{t}''=\frac{t''_{BX}+t''_{BIX}}{2},\ °C \tag{8}$$

where $t''_{вх}$,$t''_{вых}$–air temperature at the inlet and outlet of the channel of the heat exchange element, for the passage of the heating air, °C.

Average temperature difference (°C), calculated at $(\Delta t_б)/(\Delta t_м)\leq1,7$, with sufficient accuracy, as the arithmetic mean temperature difference according to the formula:

$$\Delta\bar{t}=\frac{\Delta t_b+\Delta t_m}{2},°C \tag{9}$$

where $\Delta t_б$,$\Delta t_м$–the temperature difference of the media at the other end of the heating surface, respectively, ºC.

$$\Delta t_b=t''_{BX}-t'_{BIX},°C \tag{10}$$

$$\Delta t_b=t''_{BIX}-t'_{BX},°C \tag{11}$$

RESULTS OF THE EXPERIMENT

Table 1 shows the results of experimental studies with the subsequent determination of the main characteristics of the thermoelectric generator.

Table 1: Experimental studies results

Measured value	Symbol	Dimension	Test series number		
			1	2	3
Temperature of the heated air at the inlet of the channel	$t'_{вх}$	°C	20	20	20
Temperature of the heated air at the outlet of the channel	$t'_{вых}$	°C	27,7	28,1	29,2
Heating air temperature at the channel inlet	$t''_{вх}$	°C	42,8	55,1	63,8
Heating air temperature at the channel outlet	$t''_{вых}$	°C	40	50	60
Air velocity in the channel for the passage of the heated air medium	$\bar{\omega}_{наг}$	m/s	5,1	5,1	5,1
Air velocity in the duct for the passage of the heating air	$\bar{\omega}_{гр}$	m/s	1,1	1,1	1,1
Voltage	V	V	25	26,3	27,5
Electric current intensity	I	A	3,97	4,1	4,25
Electrical power	N	W	99,4	107,6	116,9

Thus, the results of experimental studies of a thermoelectric generator clearly show the fundamental possibility of obtaining thermoelectricity in the process of utilization of low-potential thermal energy of waste gases and ventilation emissions.

Average temperature in the heated channel (5), °C:

$$\bar{t}' = \frac{40+42,8}{2} = 41,4°C$$

Average temperature in the cold channel (8), °C:

$$\bar{t}'' = \frac{20+27,7}{2} = 23,9°C$$

The thermophysical properties of air are determined at a pressure of P=1.013103 Pa according to reference data at a temperature of +41.4°C:

$$\lambda_1 = 0,0277 W/m^2 °C$$

$$\upsilon_1 = 17,1 \cdot 10^{-6} m^2/s$$

$$Pr_1 = 0,699$$

Thermophysical properties of air are determined at a pressure of P=1.013103 Pa according to reference data at a temperature of +23.9°C:

$$\lambda_1 = 0,0262 W/m^2 °C$$

$$\upsilon_1 = 15,43 \cdot 10^{-6} m^2/s$$

$$Pr_1 = 0,702$$

The calculation of the equivalent channel diameter is made according to the formula, m:

$$d_i = \frac{4 \cdot S}{P} \quad (12)$$

where S is the cross-sectional area, m²; P-channel perimeter, m.

Heated channel equivalent diameter:

$$d_1 = \frac{4 \cdot (0,27 \cdot 0,05)}{2 \cdot (0,27+0,05)} = 0,08m$$

Cold channel equivalent diameter:

$$d_2 = \frac{4 \cdot (0,27 \cdot 0,05)}{2 \cdot (0,27+0,05)} = 0,08m$$

Reynold's criterion:

$$Re_1 = \frac{w_1 \cdot d_1}{v_1} \quad (13)$$

$$Re_1 = \frac{5,1 \cdot 0,08}{17,1 \cdot 10^{-6}} = 23860$$

$$Re_2 = \frac{1,1 \cdot 0,08}{15,43 \cdot 10^{-6}} = 5703$$

With the calculated Reynolds criterion, the regime is turbulent; therefore, the criterial Nusselt equation will have the form:

$$Nu_{hc} = 0,037 \cdot Re_1^{0,8} \cdot Pr_1^{0,43} \quad (14)$$

$$Nu_{hc} = 0,037 \cdot 23860^{0,8} \cdot 0,699^{0,43} = 100,2$$

Calculation of the coefficient of heat transfer from air to the inner wall of the pipe α_1, W/m² °C:

$$\alpha_1 = Nu_1 \cdot \frac{\lambda_1}{d_1} \quad (15)$$

$$\alpha_1 = 100,2 \cdot \frac{0,0277}{0,08} = 34,7 W/m^2 °C$$

Grash of criterion:

$$Gr = g \cdot d_2^3 \cdot \frac{\left[\left(\frac{1}{273+t_e}\right) \cdot (t_e - t_x)\right]}{v_2^2} \quad (16)$$

$$Gr = 9,81 \cdot 0,08^3 \frac{\left[\left(\frac{1}{273+41,4}\right) \cdot (41,4-23,9)\right]}{(17,1 \cdot 10^{-6})^2} = 9,56 \cdot 10^5$$

Nusselt criterion equation:

$$Nu_2 = 0,5 \cdot (Pr \cdot Gr)_2^{0,25} \quad (17)$$

$$Nu_2 = 0,5 \cdot (0,699 \cdot 9,56 \cdot 10^5)^{0,25} = 14,3$$

Calculation of the heat transfer coefficient (19) from the outer surface of the pipe to thermoelectric sections α_2

$$\alpha_2 = 14,3 \cdot \frac{0,0262}{0,08} = 4,7 W/m^2 °C$$

Calculation of the heat transfer coefficient, W/(m·°C):

$$K_1 = \frac{1}{\left[\frac{1}{\alpha_1} + \Sigma \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}\right]} \quad (18)$$

$$K_1 = \frac{1}{\left[\frac{1}{34,7} + 2 \cdot \frac{0,003}{221} + \frac{0,004}{146} + \frac{1}{4,7}\right]} = 4,1 W/(m \cdot °C)$$

Heat flow calculation, W:

$$Q_h = K_1 \cdot F_{cm} \cdot (\bar{t}' - \bar{t}'') \tag{19}$$

$$Q_h = (0{,}04 \cdot 0{,}04 \cdot 25) \cdot 4{,}1 \cdot (41{,}4 - 23{,}9) = 2{,}9W$$

At a temperature of 41.4°C, the main indicators of the generated electricity are determined:

- voltage, V: U=1,0V
- electric current, mA: I=159mA

In accordance with the methodology given in [5], the auxiliary coefficient is determined by the formula:

$$m = \sqrt{1 + 0{,}5 \cdot Z \cdot (t_1^{hc} + t_2^{cl})} \tag{20}$$

$$m = \sqrt{1 + 0{,}5 \cdot 2{,}8 \cdot 10^{-3} \cdot (41{,}4 + 23{,}9)} = 1{,}01$$

The resistance of the thermoelectric converter in accordance with the certificate data is equal to R=1.5Ohm.

The maximum electric power in accordance with the certificate data is P=76W:

Efficiency factor, %:

$$\eta = \frac{Q_h}{P} \times 100\% \tag{21}$$

$$\eta = \frac{2{,}9}{76} \times 100\% = 3{,}8\%$$

To calculate the power of the cooling system of an element, it is necessary to calculate the cooling power of one Peltier element, W:

$$P_o = \frac{Q_o}{\varepsilon_{max}} \tag{22}$$

The cooling capacity of the thermoelement, taking into account losses, is determined from the expression [10]:

$$Q_o = \alpha \cdot T_x \cdot I - 0{,}5 I^2 R - \lambda (T_e - T_x) \tag{23}$$

$$Q_o = 3{,}7 \cdot 10^{-3} \cdot 41{,}4 \cdot 0{,}159 - 0{,}5 \cdot 0{,}159^2 \cdot 1{,}5 - 0{,}5(41{,}4 - 23{,}9) = -8{,}7W$$

The maximum refrigerating efficiency of the reverse cycle of the thermoelement, in which the role of the working substance is played by the electron gas and there are no irreversible losses, is calculated by the formula:

$$\varepsilon \frac{T_x}{T_e - T_x} \frac{m - \frac{T_e}{T_x}}{m+1} {}_{max} \tag{24}$$

$$\varepsilon \frac{23{,}9}{41{,}4 - 23{,}9} \frac{1{,}01 - \frac{41{,}4}{23{,}9}}{1{,}01 + 1} {}_{max}$$

$$P_o = \frac{-8{,}7}{0{,}2} = -43{,}5W$$

The heat loss that the hot junction emits will be greater than the heat that the cold junction absorbs by the amount of electricity consumption:

$$Q_h' = P_o + Q_o \tag{25}$$

$$Q_h' = -8{,}7 + (-43{,}5) = -52{,}2W$$

For this calculated in modulus value, it is necessary to select a cooling system for the Peltier element [11].

CONCLUSIONS

An experimental design of an air heater-recuperator as part of an experimental supply and exhaust system has been developed, which includes a thermoelectric EMF source operating as a result of the associated conversion of heat into electricity, which allows the utilization of low-potential heat from ventilation emissions and waste gases with a temperature from 30°C to 60°C of residential, public and industrial buildings and structures;

A mathematical model of the heat exchange process with the associated production of thermoelectricity in the utilization of low-potential heat from waste gases and ventilation emissions is proposed and investigated;

- As a result of cross-heat exchange, the temperature of the hot air at the outlet of the integrated air heater-recuperator is reduced by 6.5%.
- The amount of heat released by the hot junction corresponds to the certificate data of the semiconductor Peltier elements used in the experiment.

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