HEAT EXCHANGERS FOR UTILIZING SECONDARY ENERGY RESOURCES

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In our country, ≈2 billion tons of conventional fuel are consumed and almost 350 million Gcal are discharged into the air as a result of the combustion of this fuel. Twenty-six percent of the fuel extracted is spent providing heat for residential and public buildings. Some 63 million Gcal are used for air-conditioning buildings. In England, 30 million tons of water are evaporated every year in industry, for which $74 \cdot 10^9$ kJ of energy are consumed. In the USA, energy consumption by industry is $9 \cdot 10^{15}$ kJ/yr and 20% of this energy enters the atmosphere via the exhaust gases. The utilization of this 20% gives a savings of 4 billion dollars [1-3].

According to data provided by the Oak Ridge National Laboratory in the USA, the amount of heat ejected into the atmosphere by six industrial concerns in the USA, at a temperature not greater than 100°C, is $6 \cdot 10^{15}$ kJ/yr; $3.3 \cdot 10^{15}$ kJ/yr at 100-250°C; and, $3.4 \cdot 10^{15}$ kJ/yr at 250-1800°C. Therefore, $9.3 \cdot 10^{15}$ kJ/yr are used at a temperature level not exceeding 250°C. Seventy percent of the heat produced by a nuclear power plant must be used with cooling-water temperature equal to 18-20°C during the winter and 35-40°C during the summer.

Secondary energy resources can be used to heat air (gas), increase the temperature of steam, and to heat water (fluids).

The basic sources of secondary energy resources are: gases exhausted by industrial concerns, which are often contaminated with dust containing nitric oxides, sulfur, carbon, etc.; exhaust air from dryers, bath–laundry combines, etc., with a large quantity of steam; steam of turbines in thermal electric power stations (dry cooling towers), and water. The ocean, very deep layers of the earth, and the sun can be viewed as low-level energy resources.

Tables 1-4 illustrate the suitability of using low-level steam and gas mixtures, which represent the exhaust ventilation air.

Table 1 shows the heat and moisture indicators of buildings (auditoriums, movie theaters, palaces of culture, clubs, etc.), in which there are a large number of people. In this case, the exhaust ventilation air contains heat, which forms as a result of the activity of people [4]. There is enough such heat to heat the outside air entering the building at a rate of 20 m³/h by 22°C (the so-called minimum public health norm for fresh air [5]), which allows normal human activity.

Table 2 gives the heat and moisture characteristics of buildings of some concerns providing general public service: laundries and baths [1]. It is evident from the table that the large quantity of heat in the exhaust ventilating air can be used successfully for heating the incoming air during cold periods.

TABLE 1. Heat and Moisture Indicators of Public Buildings with a Large Number of People [1] (a cold time of the year)

Auditoriums	Sources of heat and moisture	Number of sources		Total No.		Amount of air exhausted, 10^3 m³/h	Parameters of exhaust air			Public health norm for fresh air per one person in 1 h, m³
		heat	moisture	heat, 10^3 kcal/h	moisture, kg/h		temp., °C	humidity, %	enthalpy, kcal/kg	
Theaters	People	1500	1500	188	60	30	20	60	10,19	20
Movie theaters	People	1000	1000	125	40	20	22	50	10,42	20
Clubs, palaces of culture, and other buildings	People	800	800	100	32	16	20	60	10,19	20

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TABLE 2. Heat and Moisture Indicators of Some Concerns Providing General Public Service (cold time of the year)

Heat and moisture indicators	Laundries with output of dry laundry per shift						Bath for 110 people
	500 kg		10 000 kg		15 000 kg		
	washing section	drying-ironing section	washing section	drying-ironing section	washing section	drying-ironing section	
	Plant outfitting						
Quantity of heat, 10^3 kcal/h	125 000	278	250	556	375	634	151
Quantity of moisture, kg/h	72	179	144	358	216	537	137
Amount of air removed from the building, 10^3 m^3/h	42	26	84	52	126	78	9
Temp. of air removed, °C	27	30	27	30	27	30	25
Rel. moisture content of air removed, %	75	80	75	80	75	80	75
Enthalpy of exhaust air, kcal/kg	17,1	20,63	17,1	20,63	17,1	20,63	15,76
Quantity of air removed by local pumps, 10^3 m^3/h	3,5	15,3	7	31	10,5	45,9	—
Temp. of exhaust air, °C	40	70	40	70	40	70	—
Rel. moisture content of exhaust air, %	100	90	100	90	100	90	—
Enthalpy of exhaust air, kcal/kg	40,31	171,37	40,37	171,37	40,31	171,37	—

TABLE 3. Heat and Moisture Indicators of Buildings for Housing Agricultural Animals (cold period of the year)

Heat and moisture indicators	Building for housing				
	large cattle, 1500 head	hogs, 1200 head	calves, 500 head	sheep, 1000 head	chickens, 100,000 head
Sources of heat and moisture, by weight	to 500 kg	to 200 kg	to 100 kg	to 60 kg	to 1,8 kg
Quantity of excess heat, kcal/h	1380	442	98	145	44
Quantity of moisture, kg/h	686	210	60,5	78	175
Quantity of air removed from the building, m^3/h	127	48	10	12	30
Temp. of air removed, °C	15	16	16	18	16
Rel. moisture content of air removed, %	70	75	75	75	70
Enthalpy of air removed, kcal/kg	8,16	9,1	9,1	10,33	8,77
Public health norm for fresh air, m^3/h	85	40	20	12	3,0

Table 3 summarizes the heat and moisture indicators of buildings for housing agricultural animals [1]. In spite of the low temperature of the ventilation air exhausted, it is possible to use it to heat the incoming air during the cold periods [6].

The liberation of heat in enclosures housing large cattle, per single animal with weight up to 500 kg, is such that when it is completely used, it is possible to heat the normalized quantity of incoming air by ≈30°C.

Table 4 presents the heat and moisture indicators of some industrial buildings [1]. The table shows the expediency of using the exhausted ventilation air. Thus, the operation of two paper making machines with an output of 20 tons of paper per hour involves liberation of 6 million kcal/h and 42 tons/h of moisture in the form of steam, and together with 935,000 m^3/h of air is removed from the building. The parameters of the exhausted ventilation air are as follows: temperature 60°C, relative moisture content 70%.

TABLE 4. Heat and Moisture Indicators of Some Industrial Buildings and Equipment (cold time of the year)

Enclosure	Sources of heat and moisture	Number of sources		Total number		Quantity of air exhausted, m^3/h	Temp. of air exhausted		
		heat	moisture	heat, kcal/h	moisture, ton/h		temp., °C	rel. moisture content, %	enthalpy, kcal/kg
Room for paper-making machines	Machines with an output of 10 tons per 1 h	2	2	64 million	42	935	60	70	78,01
Cardboard dryer with circulation	Output of 4.3 tons/day	1	1	$2 \cdot 10^3$ 100	2,61	46	45	80	42,99
Sizing sections of textile factories	Forming machines	4	4	908 thousand	0,538	22,8	55	50	46,57
Enclosure of textile factory	Looms in textile factories, people	900	90	451 thousand	0,01	129	30	70	18,9
Flyer frame section	Equipment	—	—	100 thousand	—	52	26	60	14,3
Section with drying kilns	Drying kilns	4	4	1 million	1,43	16	75	40	90,64
Spinning sections of textile factories	Looms, people	—	—	103 thousand	0,1	52,8	26	60	14,3

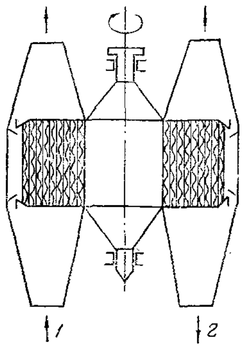

Fig. 1

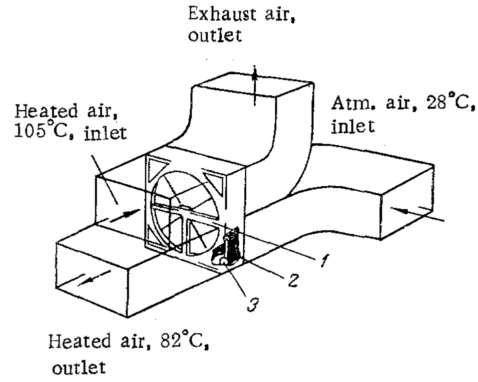

Fig. 2

Fig. 1. Rotating regenerator with horizontally positioned wheel: 1) hot gas; 2) cold air.

Fig. 2. Rotating regenerator with vertically placed wheel: 1) filter-purifier; 2) heat exchanger; 3) motor.

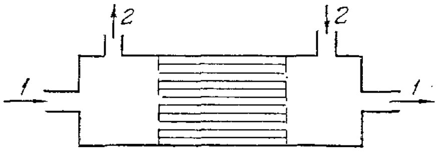

Fig. 3. Static regenerator: 1) hot gas; 2) cold air.

Of the sources of energy indicated above, special attention should be given to exhaust gases and steam, whose energy can be utilized most economically at the present time, although the potential possibilities of other forms of secondary energy resources also deserve attention. In order to utilize them, appropriate heat-exchange systems are necessary.

The following forms of heat exchangers—utilizers are well known: 1) rotating regenerators; 2) static regenerators in the form of attachments; 3) sheet regenerators; 4) sheet recuperators; 5) tubular recuperators; 6) recuperators with intermediate heat transfer agent; 7) heat pumps; 8) multichamber (power) heat exchangers with intermediate heat transfer agent; 9) static heat exchangers on heat pipes; 10) centrifugral heat exchangers on heat pipes [2, 3].

A comparative analysis of their advantages and disadvantages permits choosing correctly the heat exchanger—utilizer for any specific case.

Regenerators. Rotating and static regenerators are used in engineering. Rotating regenerators are used in heating and air conditioning systems, for drying paper and textiles. They not only permit recovering heat, but also moisture. The rotors of such heat exchangers are usually made of aluminum plates, braided wires, and ceramic plates. Aluminum foil, covered by an oxide layer, absorbs moisture well and permits recovering it. The rotors are usually rotated by electric motors with power not exceeding 0.5 kW. Figures 1-3 show the presently most widely used types of rotating recovery heat exchangers (RRHE). In the heat exchanger (Fig. 1), the rotor is made in the form of a horizontally rotating wheel made of aluminum thin-walled cylinders, covered with Al_2O_3. When hot and cold gases pass through the gaps between the cylinders, heat and mass transfer takes place between the wall and the gas. Due to the absorbing capability of Al_2O_3, it is possible to dry and moisten gas. The use of hygroscopic materials to make the rotors permits using both the enthalpy of the hot gas and the latent heat of the phase transition of water or other fluids.

Let us write the differential equation for the balance of heat for checkerwork in the form a packet of cylinders

$$\alpha A (t_g - t)\, dx d\tau = c_{ch} M_{ch}\, dx \frac{\partial t}{\partial \tau}\, d\tau$$

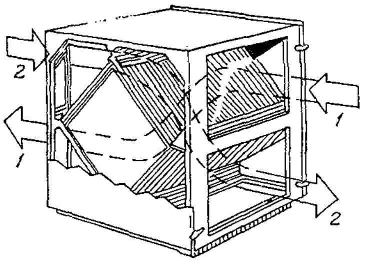

Fig. 4

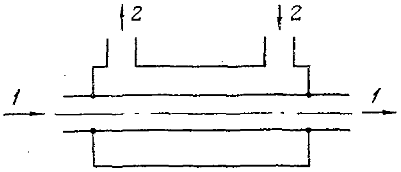

Fig. 5

Fig. 4. Plate recuperator: 1) hot gas; 2) cold air.

Fig. 5. Tubular recuperator: 1) hot gas; 2) cold air.

and for the heat-transfer agent, respectively,

$$\alpha A(t - t_g)\,dx d\tau = \rho c V dx \frac{\partial t_g}{\partial \tau} d\tau + c m d\tau \frac{\partial t_g}{\partial \tau} dx,$$

where A is the perimeter of the heat exchange surface; M, mass of the checkerwork per unit length; c, specific heat capacity of the checkerwork.

The optimum rate of rotation of the wheels is 10-20 rpm. Depending on the usable heat flux, the diameter of the wheel can be 0.5-15 m, while the thickness can be 200-1000 mm. RRHE with vertical wheels, utilizing heat fluxes up to 600 mW, are used in large thermal electric power plants. The utilization efficiency of RRHE can be 80%.

In addition to their advantages, RRHE have a number of disadvantages associated with their use: 1) high drag of the checkerwork; 2) flow of part of the hot gas into the cold gas and vice versa (up to 20%); 3) impossibility of using large pressure differentials between the hot and cold gases; 4) difficulty in cleaning dust and other contaminants from the checkerwork which greatly increase the drag of the checkerwork; 5) presence of an additional drive for rotating the rotor, etc.

Static regenerators (Fig. 3) have a stationary porous checkerwork through which hot and cold heat-transfer agents are passed alternately. Porous glass, brick, metallic plates, Rashig rings, etc., are used as the checkerwork material, which has a high heat-storage capability. Static regenerators compared to RRHE (η = 60-70%) are less efficient and have the same disadvantages. They are used mainly in industry (dryers for paper, textile, cardboard, etc.) at moderate and high temperatures.

Recuperators. At the present time, plate and tubular recuperators are widely used (Figs. 4 and 5). For them, stationary heat transfer between the two heat-transfer agents, separated by a wall, is characteristic. Plate recuperators are widely used in air conditioning and ventilation systems and can be made of paper, metal, ceramic, and glass. The plates, as a rule, have an extended surface in order to increase the surface per unit volume of the heat exchanger and to make the flow turbulent, which intensifies heat transfer. The most widely used plate recuperator is a heat exchanger made by Manters Econovent EX Company, made of aluminum plates [2]. The waviness of the thin plates is used not only to intensify heat transfer, but also to remove the condensate from the moist air. In order to intensify heat transfer and remove moisture successfully from the surface of the plates, treatment with hydrophobic substances is recommended in order to replace film condensation by drop condensation; in this case, the drops are blown off the surface by the gas flow and are trapped by traps. The method for removing the condensate from the heat-exchange surface permits cleaning contaminants and dust from it.

The precipitation of the condensate on the heat-exchange surface of metallic plates leads to undesirable corrosion and premature breakdown of the heat exchanger. In order to avoid this disadvantage, glass plate and tubular heat exchangers, which are well cleaned of contaminants and are not affected by corrosion, are used. The efficiency of the best plate and tubular recuperators is 60-70%.

Tubular recuperators (Fig. 5) are primarily used in industrial processes, chemical production, medicinal and biological industry, and are often used in high-temperature processes.

The flows in tubular recuperators move in a crossed scheme. One of the heat-transfer agents moves along tubes, while the other moves in the space between the tubes. In order to increase efficiency, tubular

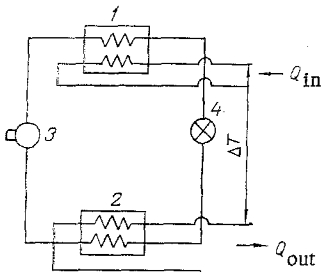

Fig. 6

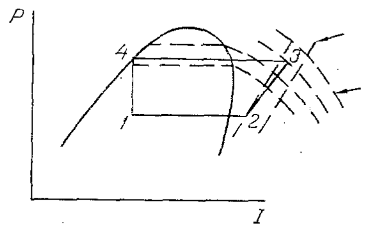

Fig. 7

Fig. 6. Diagram of a heat pump: 1) evaporator; 2) condensor; 3) compressor; 4) expansion valve.

Fig. 7. P–I diagram of the operation of a heat pump: 1) heating of evaporator; 2) increasing pressure in compressor; 3) cooling in the condensor; 4) throttling effect.

recuperators are multifilar, and fins are placed on the external surfaces of the tubes. One of the main advantages of recuperators compared to regenerators is the possibility of completely separating flows and the large pressure difference between the heat-transfer agents.

The disadvantages of recuperators include the fact that they have a high drag; the heat-transfer process has a low efficiency, since it is difficult to achieve turbulent flow within the pipes and between the plates; it is difficult to clean them of contaminants when they are being used.

The calculation of recuperators both as a check and in design analysis is based on the use of the equations of heat transfer and heat balance:

$$dq_1 = \mp G_1 c_{p_1} dt_1 = \pm G_2 c_{p_2} dt_2,$$
$$dq_2 = K(t_1 - t_2)\, dF.$$

Here dq is the effective quantity of heat transferred from the hot heat-transfer agent through the wall to the cold one; G_1 and G_2 are the mass flow rates of the heat-transfer agents; c_{p_1} and c_{p_2} are the specific heat capacities of the heat-transfer agent; K is the heat-transfer coefficient.

In the stationary regime, $dq_1 = dq_2$ and $dq = \pm G_1 c_{p_1} dt_1 = \pm G_2 c_{p_2} dt_2 = K(t_1 - t_2)dF$. The basic working equation for heat transfer has the form

$$Q = \overline{K}\Delta\overline{t}F,$$
$$\overline{K} = \frac{F_1K_1 + F_2K_2 + \cdots F_nK_n}{F_1 + F_2 + \cdots F_n}; \quad \Delta\overline{t} = \frac{1}{F}\int \Delta t dF.$$

A thermophysical calculation of recovery heat-exchange apparatus reduces to determining the surface of the heat exchanger and the magnitude of the drag. Usually, the magnitude of the heat flux, the parameters of the heat-transfer agent, the type of heat-exchange apparatus, and the direction of flow of the heat-transfer agents are given. Other variants for the calculation of the heat-exchange apparatus also exist, e.g., determining its heating efficiency, calculation of the magnitude of the parameters of the heat-transfer agents, the magnitudes of the temperatures of the heat-exchange surfaces at different locations in the apparatus.

Heat exchangers with intermediate heat-transfer agents are similar to recuperators [7]. Usually, these are tubular heat exchangers with external fins, along which the intermediate heat-transfer agent circulates either with the help of a pump or under the action of a density gradient in the gravitational force field. Single-phase and two-phase heat exchangers exist with an intermediate heat-transfer agent. Heat exchangers with a single-phase heat-transfer agent are most widely used. The main advantage of heat exchangers with an intermediate heat-transfer agent lies in the fact that they can have a large extent. Thus, for example, the part of the tubes bathed by hot heat-transfer agent can be located in one building, while the part of the tubes bathed by the cold heat-transfer agent can be located in another building. Heat exchangers with an intermediate heat-transfer agent are of great interest for creating large heat exchange systems for superheating steam Q=100-600 mW, heating air from exhaust gases from boiler works, etc. A typical example of heat exchangers with an intermediate heat-transfer agent is a heat exchanger in an internal combustion engine. The efficiency of this type of heat exchangers is usually 40-60%.

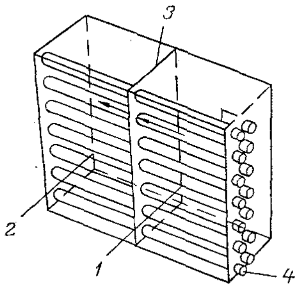

Fig. 8. Heat exchanger based on heat pipes: 1) hot gas; 2) cold air; 3) separating plates; 4) finned heat pipe.

Heat exchangers with the intermediate heat-transfer agent have the following disadvantages: 1) possibility of breaking the hermetic seal of the system and breakdown due to freezing of the heat-transfer agent, corrosion or mechanical damage of even one of the tubes; 2) not very intense internal heat transfer with fluid flow in the tubes; 3) additional expenditures of energy on pumping the intermediate heat-transfer agents; 4) narrow operational temperature range (from the triple point of the commerical heat-transfer agent to the critical point).

Heat pumps are one version of heat exchangers with an intermediate heat-transfer agent (Fig. 6). Compression-type heat pumps have a compressor and an expansion valve, connected to the vapor and liquid loops of the heat pump, as well as an evaporator and condensor, bathed by the heat-transmitting and heat-accepting media. Heat pumps, together with heat exchangers that have an intermediate heat-transfer agent, can be viewed as utilizers of secondary energy resources. Heat pumps are used to heat enclosures, using in so doing the heat in water reservoirs or in the ground, etc.

Heat pumps are widely used in refrigration systems, refrigerators, etc. The thermodynamic work cycle of the heat pump is shown in the P−I diagram (Fig. 7). The low-level heat flux is brought up to the evaporator, usually consisting of a packet of finned tubes, and causes vaporization of the refrigerant (freon, ammonia). The vapor is introduced into the compressor, where its pressure is increased by external work, and then into the condensor, consisting also of a packet of finned tubes, where the refrigerant condenses liberating a heat flux with a higher potential. The pressure of the fluid is decreased when passing through the expansion valve, before the fluid is introduced into the evaporator.

The efficiency of the heat pump is close to the efficiency of a heat exchanger with an intermediate heat-transfer agent and in the best case is 60-70%. Heat pumps are considered to be economically profitable if the ratio of the heat flux to the work expended is greater than 3. Heat pumps are indispensable utilizers of secondary energy resources in dryers and evaporators.

Air-to-air heat exchangers based on heat pipes (HEHP) can be separated into three classes:

1) HEHP_1 (process−process) for commercial processes (heating air for commercial objects, such as boilers, metallurgical furnaces, drying chambers, furnaces for burning bricks, cement, chambers for drying paint and varnish coatings, etc.);
2) HEHP_2 (process−comfort) are intended for making use of energy in heated air in heating enclosures during the winter, which permits eliminating separate boilers;
3) HEHP_3 (comfort−comfort) make use of exhaust air for heating clean cold air entering into enclosures from outside during the winter and for cooling clean hot air entering during the summer; they can be placed in schools, hospitals, institutions, swimming pools, movie theaters, etc.

Ventilation exhaust air with a temperature of 15-40°C was not previously considered to be a source of heat with sufficient energy potential. However, construction of large state and collective farm complexes which produce animal products, as well as poultry factories, requires creating new ventilation and air conditioning systems, providing the required air parameters and requiring minimum expenditures. HEHP turned out to be a convenient variant for utilizing local potential heat sources for this purpose. Comparison of their parameters with the best regenerator and recuperating heat exchangers indicates the fact that HEHP have a number of advantages, such as simplicity in organizing the counterflow systems for the air flow, possibility of controlling the temperature at the dew point in the condensation part of the heat exchanger with the use of gas-regulating heat exchangers, high reliability and durability, standardization of heat exchangers for different sizes, possibility of reversing the heating and cooling processes, no consumption of electrical energy on circulation of the working body, etc. [2, 3]. Comparison of different forms of heat exchangers according to the parameter P_C, characterizing their compactness, i.e., transfer of energy from the hot to the cold heat-transfer agent in a unit volume of the heat exchanger with a temperature differential of 1° ($W \cdot {}^\circ C/m^3$), leads to the following conclusions [2]: a heat exchanger based on heat pipes has maximum compactness ($P_C = 7200$), for a rotating regenerator $P_C = 5400$; for a heat exchanger with intermediate heat-transfer agent $P_C = 4680$; and for a plate recuperator $P_C = 4140$.

HEHP used abroad for ventilation and air conditioning of commercial and public buildings are made by the Manters Company (USA) using single-stage and two-stage schemes. The single-stage scheme is used for aggregates with an output up to 5000 m^3/h, and the two-stage scheme for higher outputs. In order to control the heat-transfer process in HEHP, they are rotated relative to the horizontal at an angle of ± 5° with the help of an actuating mechanism by command of a temperature control and by-pass of part of the cold air along the by-pass channel with the help of controlling valves. The external diameter of the exchanger is 25 mm and the number of rows varies from 3 to 7. The aggregate pays for itself when used for 10 h per day within 3-4 years.

The American company Q-Dot Corporation makes eight differently sized counterflow single-stage aggregate-utilizers with an air output from 1275 to 21,250 m^3/h. In modern well-insulated cattle breeding complexes, on poultry and hog farms [8], the use of HEHP as utilizers of the heat in outgoing air creates considerable savings both in capital expenditures and in using the complexes. In regions with relatively warm winters (with T_{av} not lower than 20-25°C), the use of HEHP on poultry farms with 10^4 birds or on hog farms, containing more than 500 hogs, makes it possible to eliminate heating of the enclosures.

HEHP are usually made in the form of several rows of finned heat pipes, placed horizontally, inclined, or vertically (Fig. 8). The heat pipes are separated into two parts by a pipe panel, which serves as a mechanical support and separates the gas conduits hermetically. The heat pipes can be from 4 to 5 m long. The heat flow, imparted along the HEHP in many cases, attains hundreds of milliwatts [9]. The HEHP have an efficiency up to 70-80%, they guarantee complete separation of the heat-exchange media, they do not have any moving systems (pumps, compressors), they are irreversible, they permit easy replacement of equipment parts when in operation, and they have the simplest and cheapest gas conduits. One of the main advantages of HEHP is the minimum drag, the presence of intense external heat exchange between the heat-transfer agents both along the hot and cold sides, and can operate in very dusty gas flows (in combination with the fluidized bed consisting of inert particles) [2, 3].

HEHP can be both static and centrifugal [3]. Centrifugal HEHP in the form of a squirrel cage, rotating inside a casing, increase the external heat transfer by 150-200% and compared to static HEHP do not require the use of a special structure inside the heat pipes. For high-temperature gas flows, the use of ceramic pipes made of SiC, Al_2O_3, etc., partially filled with alkali metals (sodium, potassium), is promising [10]. A disadvantage of HEHP is the limited operational temperature range (from the triple to critical points).

The primary area of application of HEHP together with heating and ventilating systems is utilization of the products of processing coal, solar energy, energy from nuclear power plants and boilers, and geothermal energy. The most often used materials for HEHP are aluminum, copper, and steel. Ammonia, freon, water, and diphenyl mixtures are used for the intermediate heat-transfer agent. In high-temperature HEHP, sodium, potassium, lithium, and mercury are used.

Thus, the main problems in choosing a design, constructing, and using heat exchangers are: contamination of the heat-exchange surface and degradation of the hydraulic and heat-exchange characteristics; providing for a long operational lifetime and high reliability; fighting corrosion and erosion of the heat-exchange surfaces and gas conduits; fighting the hydrodynamic vibration and nonstationary thermal stresses; ensuring low manufacturing and operational costs and possibility of maintenance and cleaning dirt from the surfaces; and ensuring compactness and high efficiency.

The analysis of different heat exchangers presented above has shown that the most promising heat exchangers for utilizing secondary energy resources are heat exchangers based on heat pipes, heat pumps, regenerators, and plate recuperators.

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