Investigation of feasibilities of heat pipe using in recuperation systems with heat excess of paper industry enterprises

I Pospelova and V Filatov
Irkutsk National Research Technical University, Russia
E-mail: pospelova@istu.edu

Abstract. The investigation was aimed to increase the energy efficiency of ventilation systems for the pulp and paper industry with an excess of heat in the technological process. The economic and thermal effect is achieved through the use of heat recovery systems based on the principle of phase transition and heat pipe. The study concluded that it will also help to solve environmental problems of paper industry.

1. Introduction and Background
There are facilities of the pulp and paper industry with excess heat during paper drying processes. A waste heat is lost in the atmosphere. The aim of the research was to achieve optimal characteristics in the heat recovery systems to increase the energy efficiency of the pulp and paper industry with excess heat in the drying process. An analysis was conducted of works devoted to the study of methods of transfer of thermal energy with excess heat. The methods of heat energy transfer in drying processes were analyzed and the most efficient was selected from them [1,4-9]. According to the results of the analysis of works that describe various methods of heat exchange, the most efficient method of heat transfer was chosen with the evaporation-condensation phase transition, since its potential for transferring thermal energy is much higher than in others. As a result of the analysis, a system with heat pipes was selected, which operates according to the principle of the evaporation-condensation phase transition. It does not use mechanical parts, moving parts that need to be changed after the period of use.

2. Materials and Methods
The design of the “heat pipe” is shown at the Fig. 1. It is a tube with a small amount of liquid, on the inner wall of which a wick is located, and air is pumped out of the tube. At low pressure, water begins to boil at a sufficiently low temperature.

"Heat pipe” has the following principle of operation - the lower end of the tube is heated, causing the process of evaporation of the liquid, the steam rises to the cold end of the pipe, where it condenses and returns to the evaporator under the action of capillary forces.
At the second stage of the study, the theoretical part for calculating the heat pipe is described, including the factors for its efficient operation, the technique for selecting the material, the working fluid, etc.

The effective operation of the heat pipe depends on a number of parameters and conditions, the first of which is the choice of working fluid.

To select the optimal working fluid used in the heat pipe, the quality criterion $M$ was introduced, which characterizes the maximum heat transfer capacity of the fluid.

The quality criterion $M$, kW / cm$^2$, is calculated according to the following formula:

$$M = \frac{\sigma_l \cdot \rho_l \cdot L}{\mu_l},$$

where $\sigma_l$ is the surface tension of the fluid, mN / m; $\rho_l$ — density of the liquid, [kg / m$^3$]; $L$ is the latent heat of vaporization of the liquid, kJ / kg; $\mu_l$ is the dynamic viscosity of the fluid, mPa * s.

But the effective work of the heat pipe (its heat transfer capacity) is limited by the following conditions:

1. The possibility of achieving steam sound speed, $QS(\text{MAX})$, kW
2. Restriction caused by the entrainment of liquid by the flow of steam, $QE(\text{MAX})$, kW. Boiling limit, $QB(\text{MAX})$, kW
3. Capillary restriction, $QC(\text{MAX})$, kW

To select the optimal working fluid used in the heat pipe, it is necessary to calculate the quality criterion $M$, which characterizes the maximum heat transfer capacity of the fluid.

The results of the calculations are shown in Table 1.

**Table 1.** Quality criterion $M$.

| Type of substance | $M$, kW/m$^2$ | $\rho_l$, kg/m$^3$ | $L \times 10^6$, J/kg | $T$, K | $\sigma^*102$, N/m | $\mu^*105$, Pa*s |
|-------------------|---------------|---------------------|----------------------|-------|------------------|------------------|
| Acetone           | 2565.64       | 689.6               | 0.472                | 373.15| 1.34             | 0.17             |
| Ammonia           | 1143.21       | 455.1               | 0.699                | 373.15| 0.9              | 0.25             |
| Ethanol           | 3488.45       | 714.7               | 0.809                | 373.15| 1.96             | 0.33             |
| Water             | 45503.70      | 958.0               | 2.258                | 373.15| 5.89             | 0.28             |
Several types of working fluids were calculated and, based on the results of calculations, it was determined that water has the highest value of the quality criterion, and accordingly it is taken as a working fluid. Next, the material was selected pipe and wick.

Compatibility of materials and working fluids has already been investigated by Baseulis and Filler through experiments. The results of their research and will focus on the case of selection of compatibility. As the material of the pipe and the wick we accept copper, due to the high coefficient of thermal conductivity, as well as with water [2]

Next, the factors limiting the maximum heat transfer capacity of the pipe are calculated. The results of the calculations are presented in Table 2.

Table 2. Results of the calculations.

| Heat transfer limitations | Pipe length, m |
|--------------------------|---------------|
| QC(MAX), kW              | 0.2           |
|                         | 0.3           |
|                         | 0.5           |
|                         | 0.7           |
|                         | 1             |
| QS(MAX), kW              | 2751.80       |
|                         | 2751.80       |
|                         | 2751.80       |
|                         | 2751.80       |
|                         | 2751.80       |
| QE(MAX), kW              | 16.75         |
|                         | 16.75         |
|                         | 16.75         |
|                         | 16.75         |
|                         | 16.75         |
| QB(MAX), kW              | 0.68          |
|                         | 1.35          |
|                         | 2.03          |
|                         | 3.38          |
|                         | 4.05          |

From all four calculated values of the limitations of the heat pipe for water, the smallest Q value is chosen, which, accordingly, will be the maximum limit of the heat transfer capacity of this heat pipe.

The capillary heat capacity limitation, QC, MAX, is the smallest of all calculated power limitations, respectively, this will be the maximum limitation of the heat transfer capacity of a given heat pipe.

Of all calculated pipes, the most effective pipe is 0.2 m long, since it has the highest capillary thermal capacity limitation value, which is QC,MAX = 0.310.

3. Experimental Section

An experiment was conducted with a heat-recovery unit consisting of heat pipes, used in the general ventilation system of the KDM-1 workshop in Bratsk. The heat recovery plant, shown schematically in Fig. 2, is a chamber with 300 thermal copper pipes, collectors for collecting thermal energy from exhaust air from the workshop and its subsequent transportation to a plate heat exchanger to heat the incoming air entering the KDM-1 shop.

For the general ventilation exchange of the KDM-1 workshop, the supply and exhaust air supply system with the experimental heat-recovery unit is used. Also in the supply and exhaust system there is an electric heater for preheating the supply air before the heat recuperator and a water heater for reheating the supply air after the heat recovery.

When designing the heat recovery unit, the following design parameters of the indoor air were adopted: internal air temperature during the cold period - plus 20 °C; temperature of exhaust air during the cold period - plus 35 °C. The following design characteristics for heat pipes characteristics are given in the table 3.

Table 3. Design features of heat pipes

| Working fluid | Water |
|---------------|-------|
| Type of pipe wick | Copper |
| Pipe length, m   | 0.2   |
| Diameter of the steam channel, m | 0.025 |
| Diameter of the steam channel, m | 0.0201 |
| Internal diameter of the pipe body, m | 0.0221 |
| Pipe angle φ, hail | 45 |
| Wick thickness, m | 0.001 |
At the figure 2 the scheme of heat-recovery installation is showed

![Diagram]

**Figure 2.** Scheme of heat-recovery installation.

The supply air was preheated in an electric heater from -41 °C to -30 °C. Next, the air is heated in a heat exchange installation of heat pipes, the inlet air temperature at the inlet is -30 °C, at the outlet + 1° C. The temperature of exhaust air at the inlet was + 35 °C, at the outlet + 1° C. The jets of heated exhaust air from the workshop are directed to the cold end of the heat pipes, the air heats the working fluid in the tube, after which it boils, rises through the tube and transfers thermal energy to the heat collectors from the pipes of larger diameter. Aqueous 30% ethylene glycol solution from the collectors enters the plate heat exchanger, where it heats the cold exhaust air. After that, the supply air is heated in a water heater from + 1 °C to + 20 °C.

According to the results of the experiment, the average daily amount of heat that was removed to transfer using a heat-recovery unit was 0.019 GCal / h or 22.3 kW.

In the case of the use of a forced-air exhaust system with a direct heating method through a water heater, 41 kW of heat would be required, which is 2.4 times higher than the heat consumption using heat recovery + the heat carrier flow increases to 1.45 m³ / h versus 0.5 m³ / h in the case of heat recovery and the metal intensity of the heater. Compared to using the direct method of air heating, the savings in thermal energy would be 60%.

4. Results and Discussion

The cost of the air handling unit without heat recovery is 175 thousand rubles. The cost of the air handling unit with heat recovery based on heat pipes will be 225 thousand rubles.

According to the results of the study, it can be concluded that the installation of heat recovery based on heat pipes is effective and expedient for general exchange, and also, possibly, for technological ventilation.

In the process of solving these problems, the following effects were achieved:
- in the case of application of the developed installation, the consumption of thermal energy was reduced by 2.4 times;
- reduced water consumption by 2.9 times.

5. Summary and Conclusion

Thus, energy efficiency of ventilation systems for the pulp and paper industry with an excess of heat in the technological process by recirculated flows using and heat pipes. The utilization of waste heat will solve environmental problems in the development of energy solutions. This can give significant economic benefits and resource savings.

References

[1] Vasiliev L L, Grakovich L P, Khrustalev D K 1988 Heat pipes in systems with renewable energy sources (Minsk: Science and technology) p 159
[2] Dan P D, Ray D A 1979 Heat pipes: Trans. from English (Moscow: Energy) p 272
[3] Ivanovsky M N, Sorokin V P, Yagodkin I V 1980 Technological bases of heat pipe (Moscow: Atomizdat) p 158
[4] Jouharaa H, Chauhana A, Nannoua T, Almahmouda S, Delpheca B, Wrobelb L C 2017 Heat pipe based systems Adv. and appl. Energy 128 1 pp 729–754
[5] Kim K M, Bang I C 2017 Heat transfer characteristics and operation limit of pressurized hybrid heat pipe for small modular reactors Appl Therm Eng 112 pp 560–571
[6] Vasiliev L 2005 Heat Pipe in Modern Heat Exchangers Appl Therm Eng 25 1
[7] Ivashov E N, Fedotov C D 2014 Heat pipes application in nanotechnology Adv. in curr. Nat. sc. 1 pp 48–51
[8] Pospelova I 2017 Determination of Optimal Heat-Storage Thickness of Layer for "Smart Wall" by Methods of Nonlinear Heat Conduction Equations for Phase-transition IOP Conf. Ser.: Mater. Sci. Eng. 262 p 012031
[9] Pospelova I, Pospelova M, Bondarenko A and Kornilov D 2018 Results of thermal modeling of Smart Energy Coating with phase-transition material for independent electricity generation J. Phys.: Conf. Ser. 1015 p 032108
[10] Greco A, Cao D, Jiang X, Yang H 2014 A theoretical and computational study of lithium-ion battery thermal management for electric vehicles using heat pipes J Power Sources 257 pp 344–355
[11] Tetuko A P, Shabani B, Andrews J 2016 Thermal coupling of PEM fuel cell and metal hydride hydrogen storage using heat pipes Int J Hydrogen Energy 41 pp 4264–4277
[12] Liu Y, Wang H, Prasad A K, Advani S G 2014 Role of heat pipes in improving the hydrogen charging rate in a metal hydride storage tank J Hydrogen Energy 39 pp 10552–10563
[13] Chung C A, Chen Y-Z, Chen Y-P, Chang M-S 2015 CFD investigation on performance enhancement of metal hydride hydrogen storage vessels using heat pipes Appl Therm Eng 91 pp 434–446
[14] Qu J, Li X, Cui Y, Wang Q 2017 Design and experimental study on a hybrid flexible oscillating heat pipe J Heat Mass Transf 107 pp 640–645
[15] Greco A, Cao D, Jiang X, Yang H 2014 A theoretical and computational study of lithium-ion battery thermal management for electric vehicles using heat pipes J Power Sources 257 pp 344–355