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Study of thermal properties in an annular heat pipe

Laziz Ochilov *

Department of Physics, Bukhara State University, 200117, M. Ikbol st., Bukhara, Uzbekistan.

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Abstract

Based on the results of research conducted on the annular heat pipe, this article analyzes the processes of heat and mass exchange occurring within it, as well as its economic and environmental indicators. The research findings indicate that the efficiency of the annular heat pipe ranges from 25% to 32%, depending on environmental conditions. The payback period of the equipment varies between 2.5 and 8 years, while the annual reduction of harmful gas emissions into the atmosphere is estimated at 111 kg. When the proposed heat pipe is installed on building walls, the heat transfer coefficient of the walls can increase by up to 3.2 times, depending on the level of thermal insulation.

Keywords: Heat Pipe; Heat Transfer; Energy Saving; Working Fluid; Evaporator; Condenser

1. Introduction

Fossil energy sources are rapidly decreasing [1], 20-40% of the produced energy is used to provide energy consumption of residential buildings [2], greenhouse gases emitted from buildings make up almost a third of the total amount [3], the large amount of energy [4] and virtual water [5] used in the production of construction materials for buildings remains a factor in causing environmental problems related to energy and global climate changes. .

If we take into account that the solar radiation falling on the earth is 3.0×10^{24} J per year [6], it can be seen that it is possible to partially cover the energy consumption of residential buildings using active and passive solar heating systems [7]. The use of solar heat pipes in buildings is also becoming more popular every year [13]. The first research on heat pipes was initiated by Gaugler in 1942 [14], and later developed by Grove in the 1960s [15]. As can be seen from Figure 1, the number of scientific and research works devoted to the use of heat pipes to increase the energy efficiency of buildings is increasing year by year.

The heat pipe consists of three main parts: the working fluid, the capillary or capillary structure, and the container [16]. The heat pipe consists of three parts depending on the heat processes taking place in it: the evaporator, the adiabatic region and the condenser (condensate forming part) [16,17]. According to the structure of the heat pipe, it is divided into two types: traditional heat pipes and ring-shaped (pulsating) heat pipes [16,17,18]. In terms of working principle, there are types of heat pipes such as gravity heat pipes, capillary heat pipes and rotary ones [18].

The integration of the heat pipe in residential buildings significantly reduces the heat energy consumption. In this work, the results of the research on the annular heat pipe were shown. Experiments were conducted in natural conditions. In experiments and calculations, the useful performance coefficient of the heat pipe, the cost recovery period, and the annual reduction of gases released into the atmosphere were calculated.

* Corresponding author: Laziz Ochilov

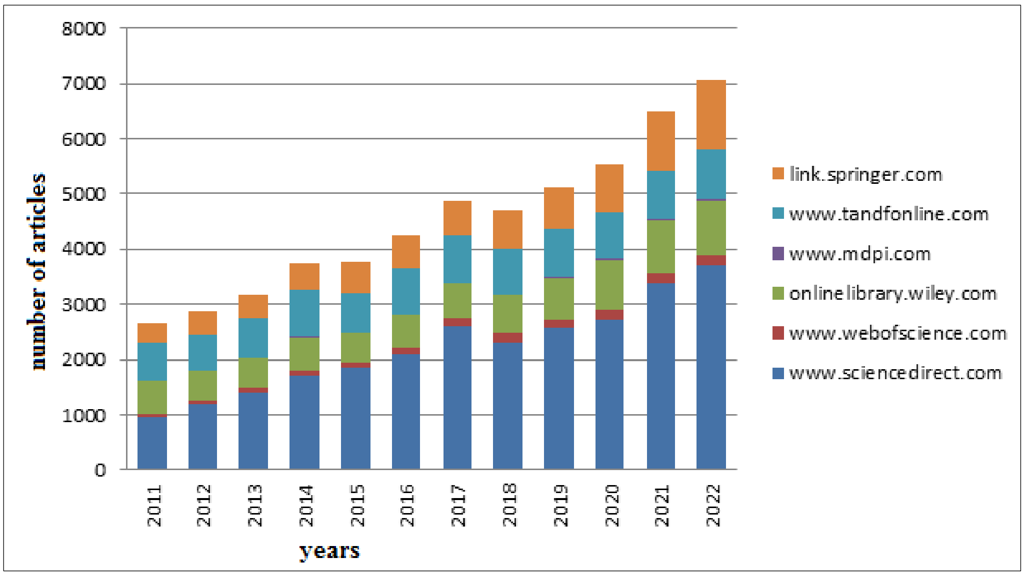

Figure 1 The number of articles published in international scientific databases on heat pipes

2. Material and methods

2.1. Device description

In this study, the thermal properties of annular heat pipes were studied (Fig. 2) [19]. The function of the proposed heat pipes is to convert solar energy into heat energy and transfer it into the building. At the same time, it consists in the accumulation of heat energy in the walls of the building.

The heat pipe is made of copper pipes according to the scheme in Fig. 2. The device consists of 3 parts, the 1st part is called the vaporizer. This part of the device consists of a total of 30 pipes with a length of 45 cm and an internal diameter of 8 mm, located at a distance of 3.4 cm from each other. The condenser part is connected to the evaporator part with a 34 cm pipe with an inner diameter of 10 mm. Part 2, the condensation part, consists of 26 pipes with a length of 42 cm and an internal diameter of 6 mm, connected to each other with a pipe with a diameter of 10 mm and a length of 28 cm. In the condensation part, steam gives its energy and turns into condensate (liquid).Part 3 is an adiabatic part that combines parts 1 and 2 above. This part consists of an insulated rubber tube 30 cm long.

The sun's rays fall on the outer (evaporator) part of the heat pipe and are absorbed by it. Absorbed sunlight is converted into heat energy in the pipes and transferred to the liquid inside the pipes. As the temperature of the liquid increases, the intensity of its evaporation also increases, and the particles flying from its free surface move upwards. The vaporized liquid moves through the pipe and passes to the condenser installed inside the wall, where it condenses. In the process of condensation, liquid vapors give their energy to the pipe, and the pipe, in turn, transfers the heat inside the building to the room air by convection and radiation.

2.2. Calculation method

Heat pipes are characterized by parameters such as heat transfer coefficient, equivalent heat transfer coefficient, useful work coefficient [21]

$$k_h = \frac{4\lambda_h L}{d_o^2}\left\{\left[\frac{\ln(d_o/d_i)}{2e} + \frac{\lambda_h}{\alpha_e d_i e} + \frac{\lambda_h}{\alpha_c d_i c} + \frac{\ln(d_o/d_i)}{2c}\right]^{-1}\right\} \quad \ldots\ldots \quad (1)$$

where $k_h$is the heat transfer coefficient of the heat pipe, W/(m^2·°C); λ_h- coefficient of thermal conductivity of the heat pipe, W/(m·°C); L- the length of the heat pipe, m; d_o, d_i - external and internal diameter of the heat pipe, m; α_e, α_c -- heat transfer coefficient by evaporation and condensation, W/(m^2·°C).

$$\alpha_e = 0.32\left(\frac{\rho_l^{0.65}\lambda_l^{0.3}Cp_l^{0.7}g^{0.2}q_e^{0.4}}{\rho_v^{0.25}h_{fg}^{0.4}\mu_l^{0.1}}\right)\left(\frac{P_{sat}}{P_a}\right)^{0.3} \quad \ldots\ldots \quad (2)$$

where ρ_l, λ_l, μ_l, Cp_l, h_{fg} are the density of the liquid in the heat pipe, kg/m3; heat transfer coefficient, W/(m·°C); dynamic viscosity coefficient, Pa·s; specific heat capacity, J/(kg·°C); specific heat of evaporation, J/kg; g - acceleration of free fall, m/s^2.

$$\alpha_c = 0.943 \left\{ \frac{\rho_l g \lambda_l^3 (\rho_l - \rho_v) \left[h_{fg} + 0.68 Cp_l (T_{sat} - T_{ex}) \right]}{\mu_l L_c (T_{sat} - T_{ex})} \right\}^{\frac{1}{4}} \quad \dots\dots \quad (3)$$

where T_{ex} is the temperature of the outer surface of the condensing part, °C; L_c- length of the sealing part, m.

Heat flow from the evaporation section

$$q_e = \frac{T_{av} - T_{sat}}{\frac{1}{2\pi\lambda_h} \ln \frac{d_o}{d_i}} \quad \dots\dots \quad (4)$$

where $T_{av}$is the temperature of the outer part of the heat pipe, °C; T_{sat} is the saturation temperature of the working fluid, °C.

$$T_{av} = \left(T_o + T_{ip} \right)/2 \quad \dots\dots \quad (5)$$

where $T_o$is the temperature of the outer surface of the layer (gypsum or plaster) surrounding the outer part of the heat pipe, °C; T_{ip}- the temperature of the inner surface of the layer (gypsum or plaster) surrounding the outer part of the heat pipe, °C.

$$T_{sa} = T_a + \frac{\alpha I_T}{h_o} \quad \dots\dots \quad (6)$$

where T_{sa} is the temperature of the outer surface of the wall, °C; α - light absorption coefficient of the outer surface of the wall; I_T- total solar radiation falling on the outer surface of the wall, W/m^2; h_o- heat transfer coefficient of the external surface of the wall, W/(m^2·°C).

$$k_{eq} = \frac{k_w A_w + k_h A_h}{A_w + A_h} \quad \dots\dots \quad (7)$$

where k_{eq} is the average equivalent heat transfer coefficient for the area, W/(m^2·°C); k_w- heat transfer coefficient of the wall, W/(m2·°C); A_w- wall surface, m^2; A_h- the total cross-sectional area of the heat pipe, m^2.

Now we calculate the amount of heat transferred from the surface of the upper part of the heat pipe into the room by convection and radiation (in our case, the device is not integrated into the building, so we get the ambient temperature).

$$Q_{kn} = h_{kn} F_d (T_2 - T_a)\, \tau \quad \dots\dots \quad (8)$$

where Q_{kn} is the amount of heat supplied to the room by convection and radiation from the heat pipe, J or kW·h; h_{kn}- coefficient of heat transfer from the heat pipe to the room by convection and radiation, (h_{kn}=8 W/(m^2·°C)); F_d- wall surface, m^2.

The useful work coefficient of the heat pipe is calculated as follows

$$\eta_{is} = \frac{Q_{kn}}{I_T} \quad \dots\dots \quad (9)$$

2.3. Experimental device and measurements

The following devices were used during the experiments: universal pyronometer M-80M; temperature sensor DS18B20; Arduino Uno. Experimental studies were conducted on August 1, 2022, October 8-9, 2022 and May 31, 2023 on the territory of Bukhara State University. During the experiments, climate parameters such as ambient temperature, humidity, wind speed, and solar radiation were determined using available measuring devices and from the source [20]. The time interval of measurements is 15 minutes.

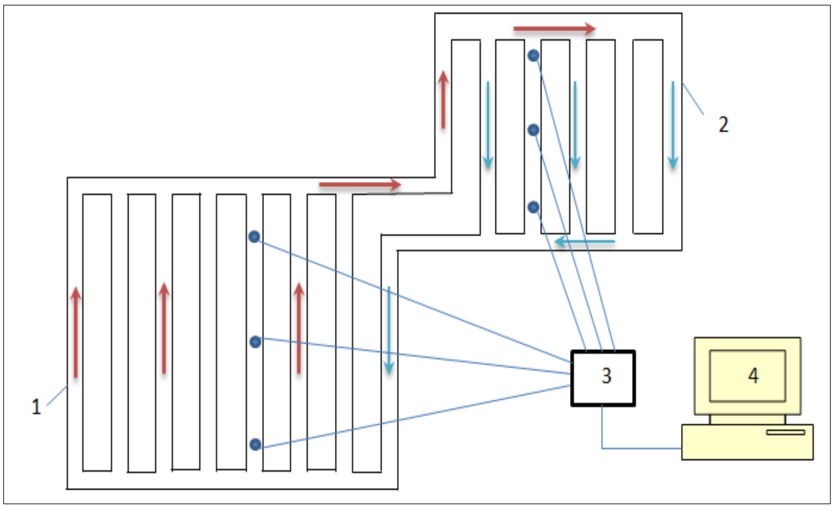

Figure 2 Location of temperature sensors installed in the device: 1-evaporator; 2- capacitor; 3- microcontroller; 4 – computer; • - temperature sensors.

Researches were conducted using the prepared annular heat pipe. Temperatures at different points of the heat pipe (shown in Figure 2) were measured over a long period of time. Based on these, the technical-economic and ecological indicators of the heat pipe were analyzed.

For this, first of all, the amount of money spent on making a heat pipe is calculated (Table 1).

The payback period of the heat pipe is determined as follows

$$n_{qm} = \frac{N_{BiPV}}{N_{kf}} \qquad (10)$$

where, n_{qm} is the period of reimbursement of expenses, days; N_{BiPV}- The price of the heat pipe (table 1), in soums and US dollars (the conversion was made with the exchange rate of the central bank on September 10 [23]); N_{kf}- The price of useful energy obtained from the heat pipe, in soums and US dollars.. In turn, when determining N_{kf}, we determine the daily value of Q_{kn} in kW·hours from equation (1) and multiply it by the price of electricity. Then it is possible to determine how much economic benefit the heat pipe brought in one day.

Table 1 The amount of money spent on making a heat pipe

№	Product name (stock name)	Unit of measure	Amount used	Amount spent, soums	Amount spent, in US dollars
1	Glass	m²	1 m²	24000	1,977398
2	Wooden plate	m²	1 m²	24000	1,977398
3	Nail	kg	0.5 kg	10 000	0,823916
4	Copper	kg	1.8	150000	12,35874
5	Polietilen	m	1.5	24000	1,977398
6	Scotch	things	1	5000	0,411958
7	Pipe	things	1	8000	0,659133
8	Transportation costs			50 000	4,11958
9	Construction costs			100 000	8,23916
Total cost				395000	32,54468

2.4. Ecological analysis

Taking into account that the studied heat pipe works using solar energy, the amount of toxic gases released into the environment will be reduced. One of the poisonous gases is CO_2, i.e. carbonic anhydride gas. The reduction of the release of toxic gases into the environment is determined by the following expression [22, 24].

$$M_{CO_2} = \frac{Q_f}{\chi \cdot \eta} K_{CO_2} \frac{44}{12} \quad \dots\dots \quad (11)$$

where ΔM_{CO_2} is the reduction mass of the amount of toxic gases released into the environment when using solar devices, kg; Q_f - useful energy obtained as a result of using the solar device, J; χ - specific heat of combustion of traditional fuel, J/kg; η is the useful work coefficient of the heat source; K_{CO_2} carbon emission coefficient for various energy sources.

The carbon emission coefficient is also different for different energy sources. The carbon emission coefficient is K_{CO_2}=0.4 for natural gas, K_{CO_2}=0.7 for coal, K_{CO_2}=0.5 for electricity and K_{CO_2}=0.5 for firewood K_{CO_2}=0.5 [22].

3. Results and discussions

Results and discussion. When calculated using equation (1), the equivalent heat transfer coefficient of the heat pipe is equal to 2.087 W/m^2°C, which is 2.1-3.2 times greater than the heat transfer coefficient of an ordinary wall, depending on the level of thermal protection.

Experiments show (Fig. 3) that 0.21 MJ or 0.058 kW·hr of useful energy can be obtained from the proposed device during the day. This amount is 1.6 kW·hr on 1 m^2 of useful surface (perpendicular surface of pipes is assumed) [23].

Table 2 Results of experiments

Time (hours, minutes)	T_1 , °C	T_2, °C	T3 , °C	T4, °C	T5, °C	T9 , °C	IT, W/m2	V, m/s	Ta, °C
10:30	50.6	48.7	53.3	22.9	25.1	25.8	756.3	1.2	31.3
11:00	58.1	55.2	60.9	26.3	28.2	29.2	861.5	1.4	32.6
11:30	58.1	55.2	60.9	26.3	28.2	29.2	861.5	1.4	32.6
12:00	63.3	59.5	66.1	28.8	30.3	31.5	841.9	2.2	33.1
12:30	67.4	64.3	70.2	31.2	32.7	34.2	859.0	2.2	33.6
13:00	70.6	67.7	73.3	33.4	34.8	36.4	880.8	2.5	33.6
13:30	72.6	69.6	75.1	35.3	36.3	38.2	880.3	2.6	33.7
14:00	73.3	70.5	75.8	36.0	36.8	38.6	882.7	2.9	33.9
14:30	71.9	69.8	75.4	36.3	36.8	38.6	880.8	3.7	34.2
15:00	70.3	68.1	73.4	36.6	37.1	38.8	855.2	3.9	34.3

where T_1, T_2, T_3 is the temperature of the collector part (lower part) of the heat pipe; T_4, T_5, T_9 - the temperature of the radiator part (upper part) of the heat pipe; T_a- ambient temperature;

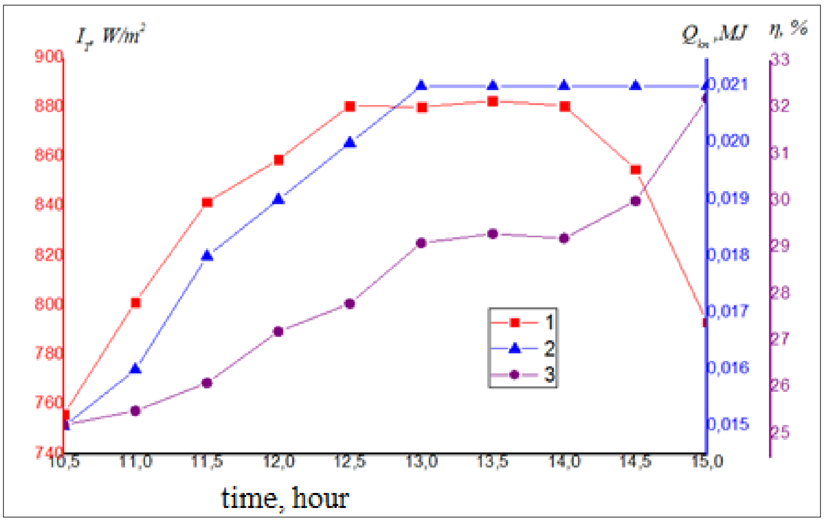

Figure 3 Calculation results for determining the thermal properties of the heat pipe**:** 1-total solar radiation falling on the outer surface of the wall, 2-the amount of heat supplied to the room by convection and radiation from the heat pipe, 3-useful coefficient of operation of the heat pipe.

The amount of money spent on heating is saved during the year by 47,900 soums per 1 m^2 of useful surface (160,000 soums for industrial enterprises). The payback period of the device, when determined using equation (3), is on average 8 years in residential buildings, and 2.5 years in industrial buildings. During the year, if the heat pipe is used as an auxiliary heat source, the release of 111 kg of CO_2 gas into the atmosphere is avoided when the heating fuel is coal.

4. Conclusions

An annular type heat pipe was studied during the research. Its main thermal properties, economic and ecological indicators were determined. Experiments were conducted in natural conditions. Experiments and calculations show that the efficiency of the studied heat pipe is 25-32%, depending on the environmental parameters, the cost recovery period is 2.5-8 years, and the annual reduction of gases released into the atmosphere is 111 kg. When the proposed heat pipe is installed on the building walls, the heat transfer coefficient of the building walls can be increased up to 2.1-3.2 times.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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