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APPLICATION OF HEAT PIPE TO ENERGY SYSTEM AT IROST

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ABSTRACT

The paper presents a review of the research on heat pipes and their applications to energy systems at Iranian Research Organization for Science and Technology. A description of the heat pipes is presented followed by a classification of them as "axial" and "co-axial". In the following sections, applications of both heat pipe types in solar collectors, heat recovery systems and power plant cooling are presented.

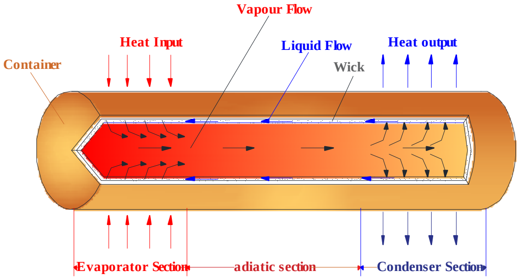
Keyword: *heat pipes, types of heat pipes, heat pipe applications, solar energy, heat recovery*

1. INTRODUCTION

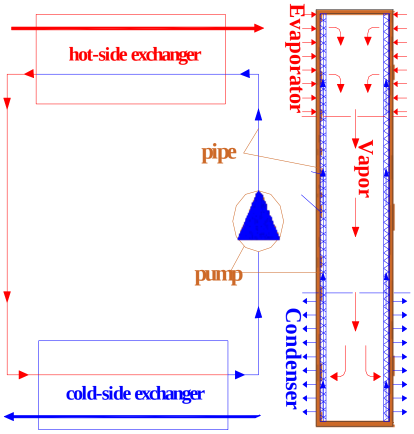
Solar energy and heat pipe heat recovery incorporated at the outset of the industrial design process can play a significant role in avoiding global pollution. In many manufacturing processes used today a tremendous amount of useful thermal energy is wasted by exhausting it into the atmosphere. In many instances, this wasted energy is not only costly but can produce undesirable thermal effect including green damage. This wasted energy can be recovered and utilized in many ways such as generating electrical power, improving the thermodynamic efficiency of a system, or simply conserving fuel.Heat pipe heat recovery systems are being used in a wide variety of industrial applications, air conditioning, heating, and ventilating systems is a heat exchanger used in duct systems to transfer thermal energy. This paper includes heat pipe solar collectors and a heat pipe heat recovery system.

1.1 Heat pipe

Heat pipes, as shown in Fig. 1(a), were developed and began to be used in many engineering applications. In the axial direction the heat pipe consists of three parts; evaporator, condenser and an adiabatic region located between these zones. The heat pipe can be constructed in plane or cylindrical geometry to describe its operation, which is similar to cylindrical geometry, the latter is illustrated in Fig. 1(a). The function of each of the three regions is: first, the evaporator where heat is supplied from an external source. Second, the condenser, where vapor condenses due to an external sink. Finally, an adiabatic section, which connects the evaporator to the condenser where vapor can transfer from the evaporator through an adiabatic vapor passage and allows liquid to return after condensation through an adiabatic wick structure. In a radial direction the heat pipe can be divided into three parts the container, wick and vapor passage. The container must be designed to withstand the vapor pressure and this decides the wall thickness for a given material. In addition, it minimizes radial temperature drop. In designing the container there must be a compromise between temperature drop and the required thickness for vapor pressure. Adjacent to the container is the wick structure. The function of the wick is to return the liquid from the condenser to the evaporator. Temperature drop for low thermal conductivity fluid can be decreased by using a high thermal conductivity wick. The wick structure must be sufficiently permeable to allow the necessary rate of liquid from the condenser to the evaporator. A heat pipe can be considered similar to a liquid-couple, indirect-transfer-type heat exchanger system. This system consists of two direct transfer type exchangers coupled together by the circulation of a suitable fluid. For the heat pipe considered, the hot-side exchanger and cold-side exchanger represent the evaporator and condenser, respectively. The coupling fluid is the heat pipe working fluid with capillary forces which are used as the pump, Fig. 1(b) (Azad and Geoola 1984).



(a) heat pipe.



(b) Liquid-coupling indirect-transfer type exchanger system and heat pipe.

Fig. 1 Basic heat pipe and thermodynamic cycle.

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1.1a Axial Heat Pipe

A heat pipe system (Dunn and Reay, 1982; Chisolm, 1971; Faghri, 1995; Fagri, 2014) is a thermodynamic device which transfers thermal energy from one location to another with a very small temperature drop. Heat pipes are ideally suited for many solar collectors, heat storage and waste heat recovery applications because of their ability to act as thermal flux transformers, their low maintenance, no moving parts, and their ability to achieve an isothermal surface of low thermal impedance. Heat pipe units can provide design flexibility when waste heat recovery systems are planned, and they can be utilized when retro-fitting existing systems.

1.1b Co-Axial Heat Pipe

A co-axial heat pipe consists of two axial tubes, with the annular space between them evacuated and filled with a small quantity of thermodynamic working fluid; cold liquid flows through the inner tube (whose outer surface is referred to as the condenser). The shoulder end pieces' act as co-axial locators and as end-seals for the chamber containing the working fluid, as illustrated in Fig. 2. The outer and inner wall of the larger tube (referred to as the absorber is lined with a wick in the form of a mesh structure, this is used to wet the surface uniformly. If heat is applied to the outer surface of the absorber tube the working fluid will evaporate and the resulting vapor will flow to the outer surface of the inner pipe, there it condenses and releases its latent heat to the cold liquid flowing inside the pipe. The net effect is for thermal energy to be transported from the inner surface of the evaporator to the outer surface of the condenser tube, and the cycle begin again. The collected condensate falls to the lower side of the absorber tube and is re-distributed by the capillary effect of the mesh. Thus, it makes it full contact with the absorber.

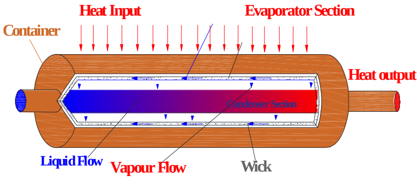


Fig. 2 A co-axial heat pipe.

Heat pipes have been known to be effective heat transfer devices for well over 50 years. They have been widely employed in various applications in industry. A variety of applications in energy systems include solar collectors, heat exchangers, heat recovery systems, peak coolers and suction heaters in a power plant. The paper present technical information regarding solar collectors design, construction, and testing at IROST in the following topics:

(a) heat pipe solar collectors

(b) heat pipe heat recovery system

2. HEAT PIPE SOLAR COLLECTOR

In this paper, two types of heat pipe solar collectors were considered:

1. Axial heat pipes solar collectors
2. Co-axial heat pipes solar collectors

2. 1. Axial heat pipes solar collectors

2.1a Type (I) Axial Heat Pipe Solar Collector

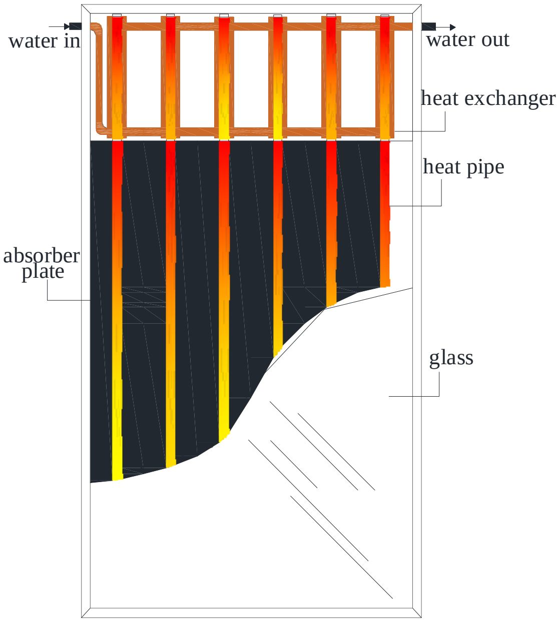
Type (I) are axial heat pipe solar collectors (AHPSC), as shown in Figs. 3(a) (Azad, 2008a), consisting of heat pipes with a wick made up of two layers of 100-mesh stainless steel screen fitted to the evaporator section for circumferential distribution of the working fluid within the evaporator. No wick is required at the condenser section since gravity will return the condensate to the evaporator section, and also the heat can only transfer from evaporator to condenser (diode action). The heat pipes are independent and function separately; therefore, if one heat pipe ceases to operate it does not have an effect on the other heat pipes (redundancy).

Fig. 3(b) illustrates a solar collector's extruded aluminum absorber plate, in which the individual heat pipe is bonded to the absorber aluminum plate and clamped to the absorber plate. The absorber plate was anodized matt black to enhance its ability to absorb heat. Fig. 3(c) illustrates the schematic of an axial heat pipe solar collector. The condenser section consists of a double-pipe heat exchanger.

The heat pipe in a solar collector must be able to transfer thermal energy from the absorber plate to the condenser section with a minimum loss of temperature.

(a) A Type (I) axial heat pipe collector (Courtesy of IROST).

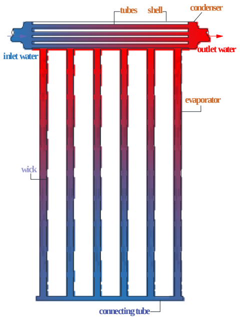
(b) Incorporation of heat pipe into the absorber plate



(c) Schematic of a Type (I) heat pipe solar collector.

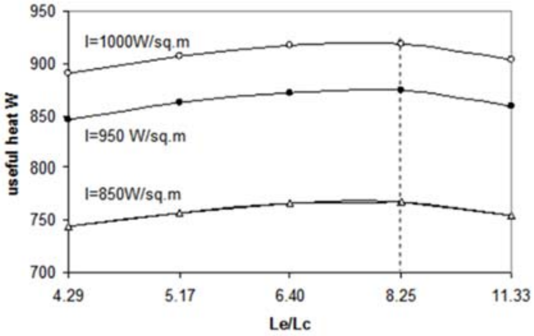
Fig. 3 Illustrations of: (a) Type (I) solar collectors, (b) absorber plate, and (c) drawing of a solar collector.

(a) Type (II) solar collector (Courtesy of IROST).



(b) Schematic of heat pipes with heat exchanger shell and tube heat exchanger.

(c) A shell and tube heat exchanger.



(d) Optimum value of Le/Lc.

Fig. 4 Illustrations of: (a) Type II solar collectors, (b) drawing of collector, (c) condenser, and (d) optimum of Le/Lc.

Azad (2008a) presents an experimental investigation of the thermal performance of a heat pipe solar collector together with a simple theoretical analysis. The results obtained from the developed theoretical model suggest an optimum heated length-cooled length ratio to reduce heat losses, absorb more heat, and increase the overall amount of useful heat. Moreover, they found sufficient condenser surface area must be provided to minimize the temperature loss at the condenser/heat exchanger. The shell and tube heat exchanger is appropriate for this purpose.

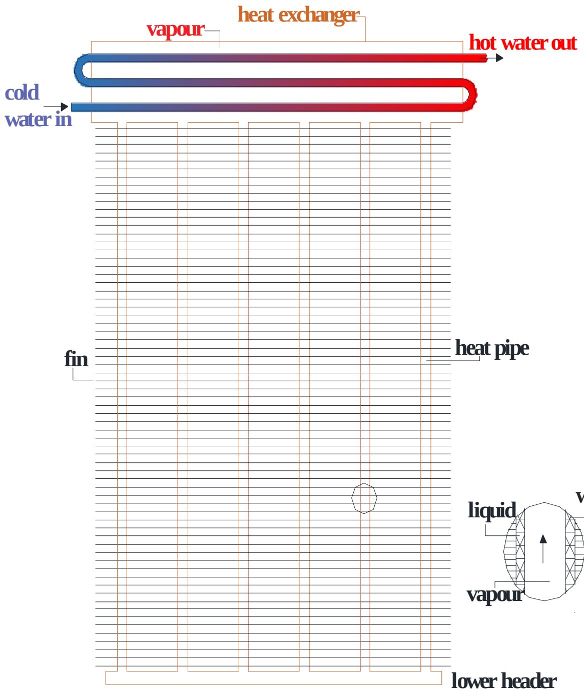
2.1b Type (II) Axial heat pipe solar collector

Fig. 4(a) and Fig. 4(b) show a Type (II) AHPSC, the absorber plate is same as the previous one. The condenser consists of a shell and tube heat exchanger connected to the upper end of the heat pipes, and the lower end of the heat pipes were connected to a tube in order to uniformly distribute the working fluid.

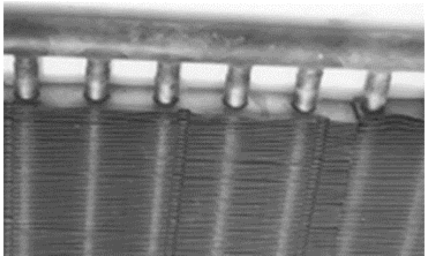
In the present design, the heat can only transfer from the evaporator to condenser section not vice versa. Fig. 4(c) shows the heat pipes connected to the shell and tube which allows the entire system to be evacuated. When heat is supplied to the absorber plate it causes the working fluid to vaporize and the vapor to move to the condenser where it condensed on the tubes. The condensate is returned to the evaporator by gravity, Azad (2012). The advantages of this type of heat exchanger is it occupied less area; hence, it absorbs more energy, and according an investigation performed by Azad (2008a) fulfills the optimum ratio of evaporator to condenser length ratio (Le- evaporator length and Lc- condenser length), Fig. 4(d).

2.1c Type (III) Heat Pipe Solar Collector

A Type (III) heat-pipe solar collector designed and constructed to collect and distribute heat by means of vaporization and condensation of a heat transfer fluid is shown in Figure 5(a). The lower section of the evaporator is interconnected by a 12.7 mm copper tube to distribute the working fluid uniformly in the heat pipes; thereby, avoiding the dry-out problem that might be experienced in traditional heat pipe solar collectors.



(a) heat pipe collector.



(b) Constructed Type (III) heat pipe absorber plate.

Fig. 5 AHPSC with a finned tube absorber.

The absorber was constructed from a continuous finned tube commonly use in low-pressure applications such as air-conditioning industries and dry-cooling towers. The tubes were expanded in order to have close contact with the fins. The upper end connected to a shell with three tube passes. Solar radiation warms the absorber plate and thermal energy is transferred by conduction through the pipe wall of the heat pipe and saturated wick to the liquid-vapor interface, where the working fluid vaporizes and the vapor leaving the heat pipes enter the shell and condenses on the outside wall of the tube passes. The condensate runs back through the shell and returns to the heat pipes under the action of gravity, (Azad, 2009 a, b).

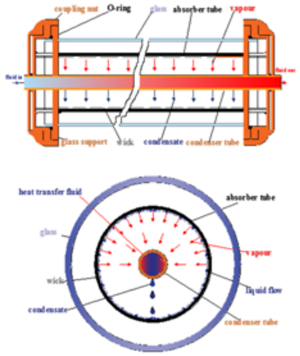
Fig. 6. illustrates the simultaneous test of the three mentioned solar collectors in conjunction with other collectors including a flow-through conventional collector.

Fig. 6 Simultaneous testing of various types of solar collectors.

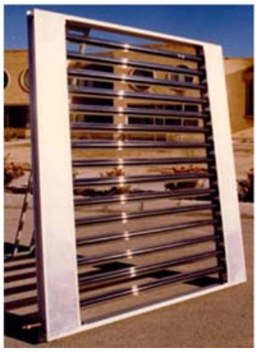
2.2. Co-Axial Heat Pipes Solar Collector

The basic configuration of a single co-axial heat pipe is shown in Fig. 7(a). The heat pipe is made up of a glass tube inside which are two co-axial copper tubes, with the annular space between them evacuated and filled with water as the working fluid; the inner tube is a water pipe (whose outer surface is referred to as the condenser). Shouldered copper end-pieces act as co-axial locators and end-seals for the wall of the larger copper tube (referred to as the absorber). The absorber is painted matt black and its inner wall is lined with a wick in the form of 100-mesh net to insure a uniformly wet surface. A glass envelope is used to protect the absorber from degradation, rain and dust. It is made from Pyrex, which maintains good strength and transmittance under high temperature. Solar energy received by the outer surface of the absorber causes the working fluid to vaporize. Vapor flows inwards towards to the outer surface of the condenser tube, where it condenses and releases its latent heat to the cold water inside the tube. The collected condensate falls to the lower side of the absorber tube and is re-distributed by the capillary effect of the mesh. Thus, it makes full contact with the hot surface of the absorber, and the cycle begins again. A co-axial solar collector with 15 heat pipes, as shown in Fig. 7(b), were constructed and tested. The advantages of this design is that the collector is independent of inclination angle allowing it to be installed on the wall in high rise buildings (Azad, 1991). This system it theory were subsequently modified by Azad (2011).

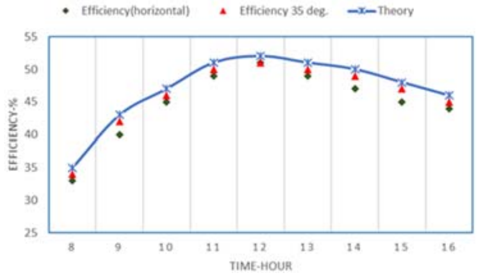
The experimental efficiencies of the collector in horizontal and tilted 35° N towards the south is calculated as the product of heat capacity rate per unit collector area and water temperature rise in the condenser tube divided by the solar irradiance as obtained by outdoor measurements is compared with a simple theoretical model in Fig. 4(c). The experimental efficiencies and the corresponding theoretical results have the same trend with significant agreement. The maximum difference between experimental efficiencies (horizontal and tilted 35°) occurs at 09:00. At 14:00 the horizontal position efficiency is 40% while the tilted position is 43% (a difference of about 3%). The experimental and the calculated hourly values of water outlet temperature (T_o(exp), T_o(theory)), inlet water temperature T_i and insolation I are plotted in Fig. 10. The left scale represents the outlet water temperature and right scale represents the solar insolation. The maximum difference between theoretical and experimental outlet water temperatures occurs at 14:00 and is due to a slight fluctuation of solar insolation. As can be observed from this figure, at 14:00 the calculated theoretical outlet temperature is 25°C while the experimental outlet temperature is 24.5°C (an absolute difference of 0.5°C).



(a) Single co-axial heat pipe.



b. Co-axial heat pipes solar collector (Courtesy of IROST).



(c) Efficiency of collector in a horizontal and 35 deg. position.

Fig. 7 A co-axial heat pipe solar collector.

3. HEAT PIPE HEAT RECOVERY SYSTEM (HPHRS)

It is possible to categorize four main application areas for waste heat recovery equipment.

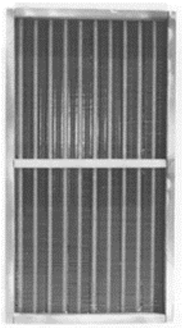
1. gas-to-gas,
2. gas-to-liquid,
3. liquid-to-gas, and
4. liquid-to-liquid.

Heat pipes are ideally suited for various types of waste heat recovery applications. The different heat pipe heat exchangers are described below

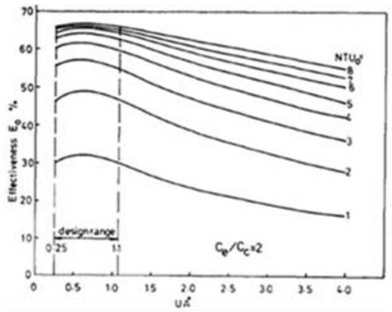
3.1.GAS-TO-GAS

3.1a Gas-to-Heat Pipe Heat Recovery System

Azad and Geoola (1984) presented a theoretical approach for the design of gravity-assisted heat pipe heat exchangers (GAHPHEs). A heat pipe heat exchanger used for air-to-air heat recovery is essentially a nest of finned heat pipes which appears similar to conventional steam coils. Each individual tube is a heat pipe and they operate independently. The arrangement of the heat pipe heat exchanger may be horizontal or tilted with hot sections (evaporators) below the cold sections (condensers). In the latter case, the gravitational force can be utilized to return the condensate to the evaporator i.e. it is 'gravity assisted'. In a gravity-assisted mode, the presence of a capillary structure is not necessary as it is in a pure capillary-drive heat pipe. Nevertheless, most gravity-assisted heat pipes do have a capillary structure in order to protect the liquid against the shear stress exerted by counter-flowing vapor and also to induce circumferential distribution of the working fluid within the evaporator section. In gravity-assisted heat pipes, relatively high rates of heat transfer can be achieved even with working fluids with a low surface tension. Hot exhaust air is passed through the evaporator sections of the heat pipes and cold air is passed through the condenser sections in the opposite direction, i.e. a counter-flow arrangement. A schematic of the GAHPHE is shown in Fig. 8(a). This study presents a theoretical approach to the design of GAHPHEs. In terms of predicting the performance of a heat e Fig. 8(b). show the variation of overall effectiveness with UA * for different values of NTU_o at $C_e/C_c = 2$, 1.33 and 1, respectively. For design purposes a rather broad design range for UA* is specified in these figures. These design ranges are based on a maximum error which is 5% of computed overall effectiveness, that occurs on the curve of $NTU_o = 1$.



(a) Gas-to-gas heat pipe heat recovery system.



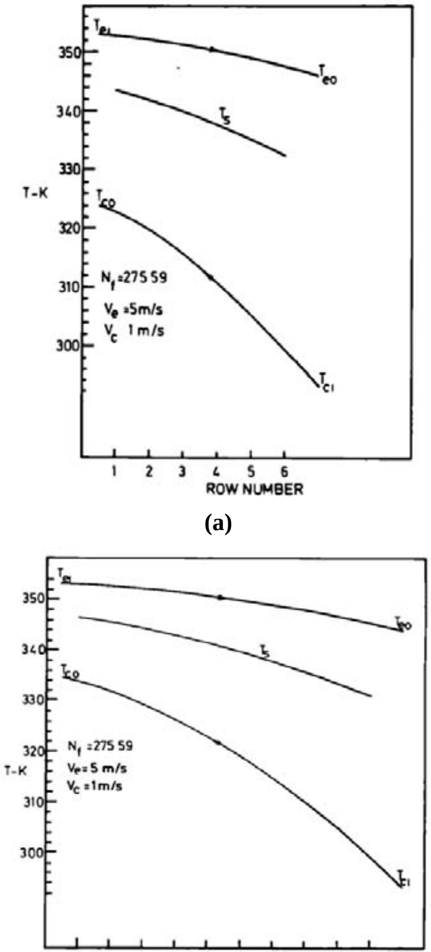
(b) Optimum design range of UA^* for C_e/C_c=2.

Fig. 8 gas-to-gas heat recovery system

3.1b. Thermal Performance of Heat Pipe Heat Recovery System

Azad et al. (1985a) developed and investigated a theoretical analysis to predict the performance of a heat pipe heat exchanger. Numerical analysis is employed to determine the performance of the heat pipe heat exchangers. Variation of overall effectiveness for six and ten rows exchangers with Ce/Cc for different values of Re_e and Re_c were investigated. For $C_e > C_c$ the overall effectiveness increases and at Ce = Cc the overall effectiveness is minimum.

In Figs. 9(a) and fig. 9. (b) the air temperature in the flow direction for both evaporator and condenser and also the saturation temperature of the heat pipe for each row are plotted. The effect of fin density on performance of the heat pipe heat exchanger was investigated. The figures show that increasing the number of fins per unit length increases the overall effectiveness.



(a)

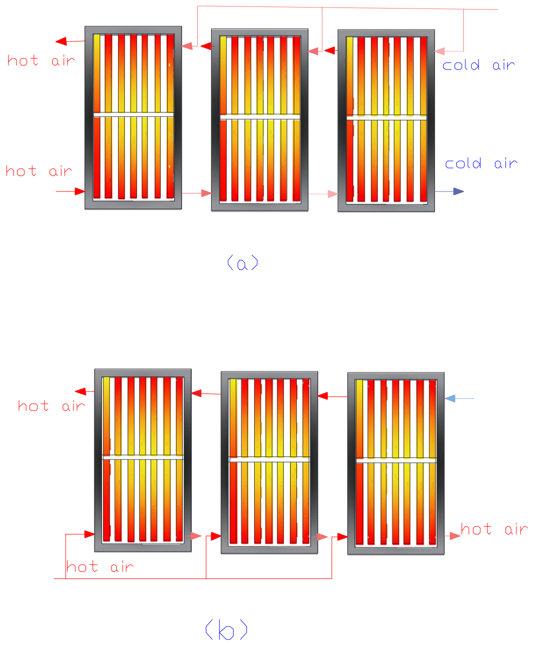
(b)

Fig. 9 Temperature distribution in flow direction, (a) for six rows (b) for ten rows.

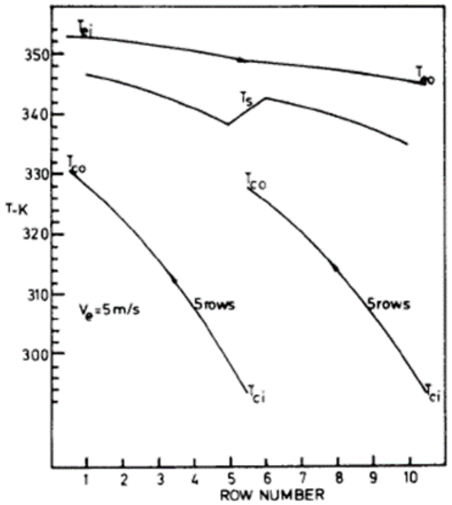
3.1c Multi-Stage Heat Pipe Heat Exchanger

(Azad et al., 1986) reported a theoretical analysis of the multistage heat pipe heat recovery system (HPHRS). In a multi-stage heat pipe heat exchanger, the system contains several units. Each individual unit is a heat pipe heat exchanger and they operate independently. The behavior of a multi-stage heat pipe heat exchanger with, flow in series in the condenser sections and parallel in the evaporator sections of the units Fig. 10a, or in the condenser sections the flows are in parallel and in series in the evaporator sections Fig. l0b, differs from that of a conventional heat pipe heat recovery system. Its performance depends on, among other factors, the number of stages and distribution of hot and cold fluid.

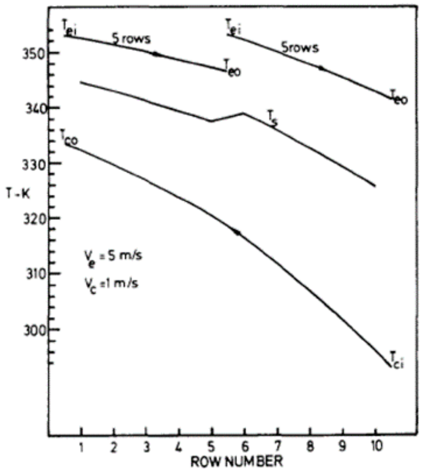
In this study, air temperature in flow direction for both evaporator and condenser and also the saturation temperature of the heat pipe versus number of rows plotted in Fig. 10(c) and Fig. 10(d).



Evaporator in (a) series and (b) parallel.



(c). Temperature distribution in the flow direction (for two stages).



(d) Temperature distributions in the flow direction (for two stages).

Fig. 10 A multi-stage heat pipe heat exchanger.

3.1d Split Heat Pipe Heat Recovery (SHPHR) system

Azad (2008b) describes a theoretical analysis of a split heat pipe heat recovery system (SHPHR). The analysis is based on an effectiveness-NTU approach to deduce its heat transfer characteristics. In this study, the variation of overall effectiveness of heat recovery with the number of transfer units is presented. In the SHPHR, the evaporator is connected to the condenser through a piping system. The condenser section is located above the evaporator so that the condensate is returned by gravity. The vapor flows through a tube (vapor line) to the condenser and condensate returns to the evaporator through a tube (liquid line) via gravity. The vapor line connects the top of the evaporator to the top of the condenser, and the liquid line connects the lower part of the condenser to the lower part of the evaporator Fig. 11. The SHPHR possesses all the main advantages of a conventional HPHR. The only difference between the SHPHR and conventional heat pipe heat recovery system lies mainly in the separation of the evaporator and condenser. In an SHPHR, the evaporator and the condenser can be located in different places.

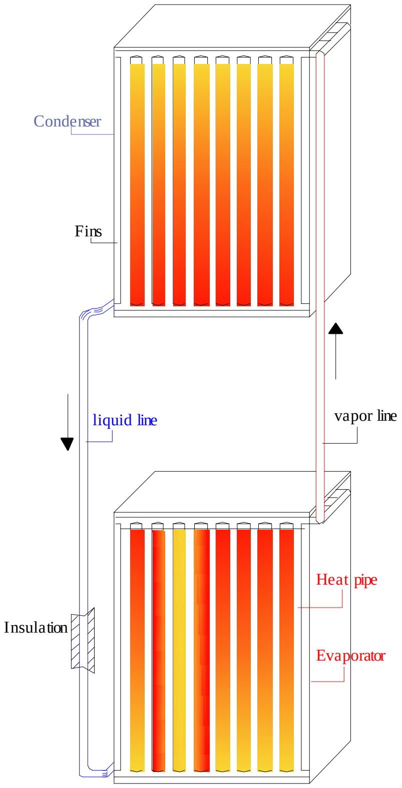


Fig. 11 A split heat pipe heat recovery system

4.2 Gas-to- Liquid

4.2a Gas-to- Liquid Heat Pipe Heat Exchanger

Azad and Gibbs (1987) studied a system consisting of a multi-row axial heat pipe heat exchanger with the condenser at the side and connected in series in a row. In this system, the condenser tube of each row is parallel to each other and joined at the ends to the tube headers (Fig. 12). Hot exhaust gas is passed across the evaporator sections of the heat pipes where the heat pipes remove heat from the exhaust gas stream and transfer it to the water in the condenser tube causing an increase in the water outlet temperature. The theoretical analysis presented in this study can be used to predict the thermal performance of an air-to-water heat pipe heat exchanger.

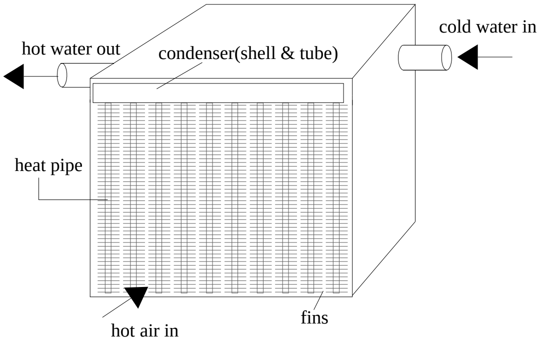


Fig. 12 An axial heat pipe heat exchanger.

In the work of Azad et al. (1985) the water-to-air heat pipe heat exchanger, as shown in Fig. 13, is essentially an array of partially finned (condenser sections only) heat pipes. The evaporator sections are enclosed in a rectangular box and the water passage is baffled with a three-pass arrangement to direct the flow across the heat pipe array to achieve a uniform temperature distribution. The cold air is arranged to pass through the condenser sections in a counter-current flow with the hot water flowing in the evaporator sections. Several potential advantages of a heat pipe in this application are low temperature drop, heat transfer and redundancy. Each unit is a self-contained pumping system and a number of failures would have no effect on the operation of the system. This study describes the analysis of the design of the water-to-air heat pipe heat exchanger. The characteristics of the heat exchanger are studied analytically to present the performance of the heat exchanger.

Fig. 13. A water-to-air heat pipe heat exchanger.

4.2b. Design of Air-to-Water Co-Axial Heat Pipe Heat Exchanger

Fig. 14 presents a schematic of a co-axial heat pipe. It consists of two pipes of different diameter and they are mounted one within the other so as to form a concentric annulus. The inner surface of the outer pipe is covered with wick material, filled with water, and permanently sealed. The operation of the heat pipe is based on the evaporation of a liquid in the evaporator section and the subsequent flow in the core toward a region of low pressure. The vapor condenses on the outer surface of the inner pipe (condenser). After the latent heat of condensation has been released at the condenser, the liquid drops to the lower section of the evaporator and then returns to the heat source through the wick by capillary pumping where it is re-evaporated (Azad and Moztarzadeh, 1985).

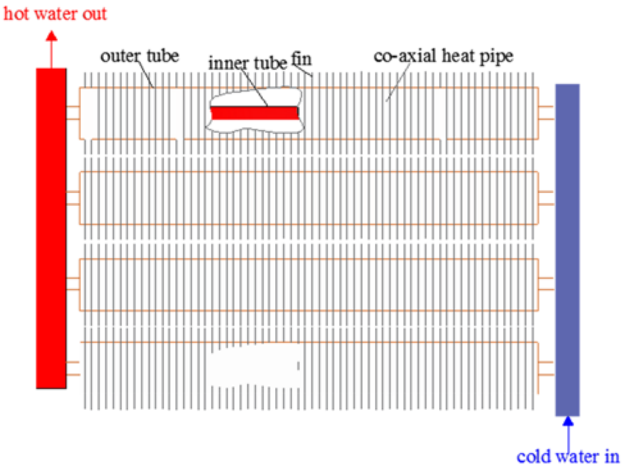


Fig. 14. Co-axial heat pipe description.

4.3. LIQUID–TO- GAS

4.3a. Auxiliary Heat Pipe Cooler in Thermal Power Plant

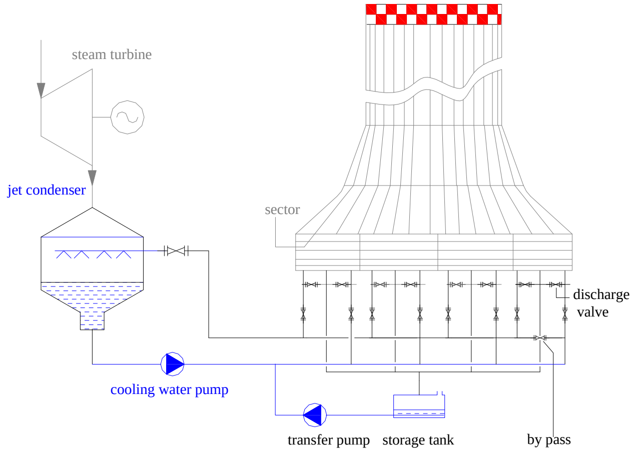
Azad and Karimeddini (1990) developed a dry cooling process for a thermal power plant in which a nominal cooling performance can be maintained even at high ambient temperature, Fig. 15a and Fig. 15b. The air cooler module is comprised of two banks of heat pipes in a Y-shaped configuration Fig. 15c and d. Each bank contains 180 heat pipes. They are mounted on a conduit through which the cooling water flows past the lower ends of the heat pipes (evaporator). The heat pipes transfer thermal energy from evaporators to condensers, and the heat is dissipated to the air by convection from the surfaces of the Forgo fins and out to the atmosphere. The amount of heat that is rejected by an air cooler is largely dependent on the air volume flow rate through the heat exchanger. A heat pipe, as a single component of HPAC (Heat Pipe Air Cooling) mesh wick, is used in the evaporator of the heat pipe to distribute liquid in the evaporator of the two-phase thermosyphon. A metal tube sheet divides the two sections and contains the necessary leak-tight seals (O-rings) for each heat pipe, these seals prevent the leakage of water and allow easy removal and replacement of heat pipe(s) from the cooler if non-functional. Heat pipe peak cooler offer three special features that offer an advantages over standard peak coolers:

i- The heat pipes are independent of one another: failure of one has no effect on the others
ii- Hot and cold sides surface are independent, since they are linked only by the heat pipe
iii- The system offers a saving of 17% in total fin area relative to a conventional arrangement

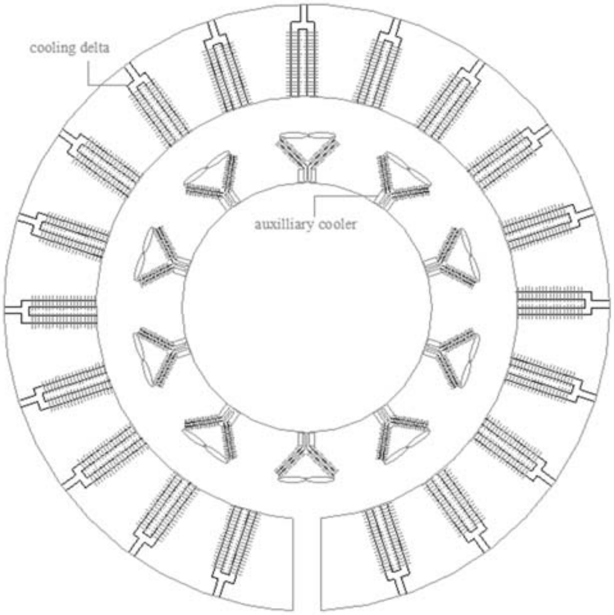
4.4. LIQUID-TO-LIQUID

4.4a Liquid-liquid heat pipe heat exchanger

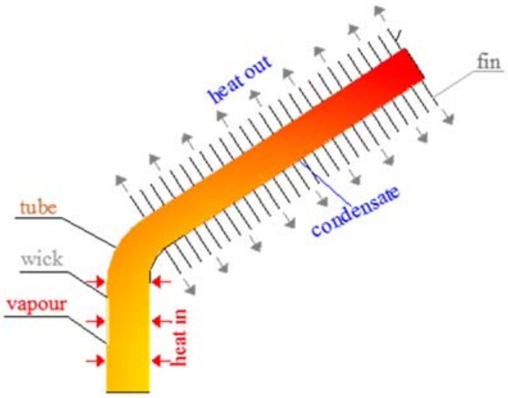
Azad (2007) reported on a heat pipe suction heater in a thermal power plant showing a heat pipe as a component in the suction heater. The heat pipe are longitudinally finned in the condenser section only, the inside surface of the pipes are lined with a mesh structure in order to distribute the working fluid and also to return the condensate from condenser to evaporator. A number of heat pipes are placed in a shell as shown in Fig. 16. The steam enters from the upper part and transfers its latent heat to the working fluid of the heat pipes then it condenses on the surfaces of the pipes and condensate is removed from lower parts of the shell. The heat is absorbed by the heat pipes to the viscous liquid causing it to increase its temperature and consequently decrease its viscosity resulting in easy flowing of liquid.



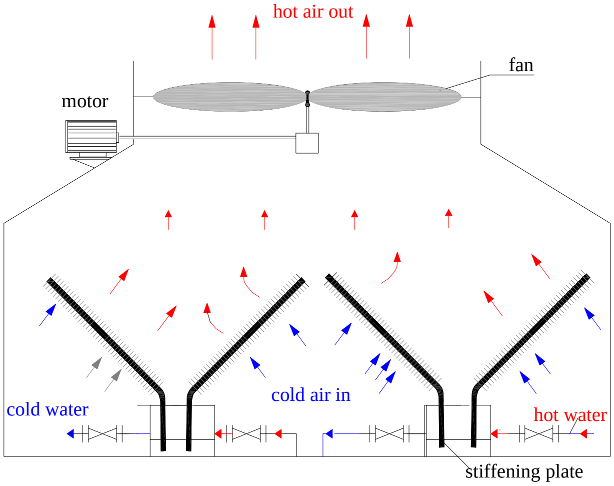
a- A dry cooling tower.



b- The plan view.



c- Heat pipe as a cooling element.



d- Auxiliary heat pipe cooler.

Fig. 15. Thermal power plant cooling system

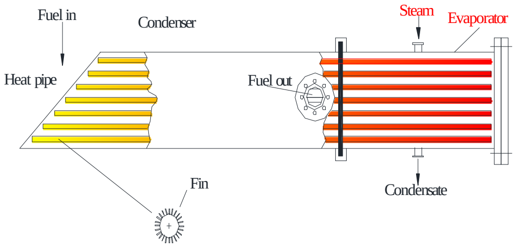


Fig.16. Heat pipe suction heater

5. CONCLUSION

The heat pipe has the potential of transferring thermal energy function in many industrial applications. An overview of two types of heat pipes, axial and co-axial is presented in this review. In this work several design of heat pipe solar collectors were presented. The last category deals with heat pipe heat recovery systems, gas-to-gas, gas-to-liquid, liquid-to- gas, and liquid-to-liquid and auxiliary heat pipe peak cooler in thermal power plant was also discussed.

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NOMENCLATURE

C_c	Flow-stream capacity rate of cold-side fluid (W/^{o}C)
C_e	Flow-stream capacity rate of hot-side fluid (W/^{o}C)
Le	evaporator length (m)
Lc	condenser length (m)
m_e	mass flow rate in condenser section (kg/s)
m_e	mass flow rate in evaporator section (kg/s)
Re	Reynolds number
Tci	cold fluid inlet temperature (^{o}C)
Tco	cold fluid outlet temperature (^{o}C)
Tei	hot fluid inlet temperature (^{o}C)
Teo	hot fluid outlet temperature (^{o}C)
Ts	heat pipe surface temperature (^{o}C)

REFERENCES

Azad, E., and Geoola, F., 1984, “A Design Procedure for Gravity-Assisted Heat Pipe Heat Exchanger,” *Journal of Heat Recovery Systems*, **4**(2), 101-111
http://dx.doi.org/10.1016/0198-7593(84)90014-6

Azad, E., and Moztarzadeh. F.,1985, “Design of Air-to-Water Co-Axial Heat Pipe Heat Exchanger” *Journal of Heat Recovery Systems*, **5**(3), 217-224
http://dx.doi.org/10.1016/0198-7593(85)90079-7

Azad, E., Mohammadieh, F., and Moztarzadeh, F., 1985. “Thermal Performance of Heat Pipe Heat Recovery System” *Journal of Heat Recovery Systems*, **5**(6), 561-570.
http://dx.doi.org/10.1016/0198-7593(85)90224-3

Azad,E, Bahar.F and Moztarzadeh,F, 1985. “Design of Water-to-Air Gravity-Assisted Heat Pipe Heat Exchanger,” *Heat Recovery Systems*, **5**(2), 89-99.
http://dx.doi.org/10.1016/0198-7593(85)90041-4

Azad, E., Mohammadieh, F. & Moztarzadeh, F., 1986. “Effect of Different Arrangement on Performance of Heat Pipe Heat Recovery” *Heat Recovery Systems*, **6**(2), 143-149.
http://dx.doi.org/10.1016/0198-7593(86)90074-3

Azad, E., Moztarzadeh, F. & Zargham, N., 1986. “An Experimental Study of a Co-Axial Heat Pipe Solar Collector”. *Journal of Heat Recovery Systems*, **6**(3), 255-258
http://dx.doi.org/10.1016/0198-7593(86)90009-3

Azad, E. and Gibbs, B.M., 1987. “Analysis of air-to-water heat pipe heat exchanger”. *Heat Recovery Systems and CHP*, **7**(4), 351-358.
http://dx.doi.org/10.1016/0890-4332(87)90097-4

Azad, E., Bahar, F., & Moztarzadeh, F.,1987, “Solar Water Heater Using Gravity-Assisted Heat Pipe.” *Heat Recovery Systems and CHP*, **7** (4), 343-350.
http://dx.doi.org/10.1016/0890-4332(87)90096-2

Azad., E. and Karimeddini, Z.K., 1990 “A New Concept of Heat –Pipe Cooling for Thermal Power Plant in High Ambient Temperatures”. *J. of the Institute of Energy*, **63**(45), 119-123

Azad, E., and Bahar, F.,1991. “Thermal Performance of a Co-Axial Heat-Pipe Solar Collector.” *Journal of the Institute of Energy*, **64**(45), 107-112.

Azad.E., 2007, “Performance Analysis of a Heat Pipe Suction Heater for Thermal Power Plant.” *Applied Mechanics Research*, **1**(1), 3-6.

Azad, E., 2008a, “Theoretical and Experimental Investigation of Heat Pipe Solar Collector”. *Experimental Thermal and Fluid Science*, **32**(8).
http://dx.doi.org/10.1016/j.expthermflusci.2008.05.011

Azad, E., 2008b, “Split heat pipe heat recovery system”. *International Journal of Low Carbon Technologies*, **3**(3), 191-202.
http://dx.doi.org/org/10.1093/ijlct/3.3.191

Azad, E., (2009a). “Interconnected Heat Pipe Solar Collector,” *International Journal of Engineering, Transactions A: Basics*, **22**(3), 233-242.
http://dx.doi.org/10.1007/s00231-011-0827-3

Azad, E., 2011, “Theoretical Analysis to Investigate Thermal Performance of Co-Axial Heat Pipe SolarC”. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung*, **47**(12), 1651-1658.

Azad, E., 2012. “Assessment of three types of heat pipe solar collectors. Renewable and Sustainable Energy Reviews,” **16**(5), 2833-2838.
http://dx.doi.org/10.1016/j.rser.2012.02.001

Azad, E., 2013. “Review: Heat pipe heat exchangers at IROST. International Journal of Low-Carbon Technologies,” **8**(3), 1-7.
http://dx.doi.org/10.1093/ijlct/cts012

Chisolm, D., 1971, *The heat pipe*. M and B Technical Library.TL/ME/2. Pub. Mills and Boon Ltd., London

Dunn, P.D., and Reay, D.A., 1982, *Heat pipes*, third ed., Pergamon Press, Oxford.

Faghri, A., 1995, *Heat Pipe Science and Technology*, 1st ed., Taylor & Francis, Washington, D.C