DESIGN AND DEMONSTRATION OF HEAT PIPE BASED WASTE HEAT RECOVERY SYSTEM

S. Venkateswarlu[1], Srinivasa Rao Gampala[2], Ambadipudi Sunil[3],

[1] *Assoc. Prof. Dept. of Mechanical, SBIT Khammam, Telangana State, India*

[2]*Asst. Prof. Dept. of Mechanical, SBIT Khammam, Telangana state, India*

[3]*Asst. Prof. Dept. of Mechanical, SBIT Khammam, Telangana state, India*

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Abstract - *A heat exchanger is a device used to transfer heat between a solid object and a fluid, or between two or more fluids. They are widely used in space heating, refrigeration, air conditioning, etc. are called as conventional heat exchanger. Where conventional heat exchangers not effectively utilized, heat pipe is used as an alternate type of heat exchanger. A heat pipe is a passive heat transfer device which transfers heat from a source to sink by alternate evaporation and condensation of fluid inside a sealed system with temperature drop of 5°C per meter length of pipe. Heat pipe is a stationary device and also it does not have any moving parts. It has three basic components the container, working fluid and the capillary structure. A heat pipe allows transfer thermal energy (heat) over a distance very efficiently. The transfer occurs quickly and with very little temperature loss across the distance. Over a six inch length, the thermal conductivity of the heat pipe can be 100 times greater than a comparable copper rod. A heat pipe is a hollow aluminum or copper tube, sealed at both ends, and filled with a capillary wicking material that is saturated with a liquid. When heat is applied to one end, the liquid at that end absorbs the heat and evaporates. The vapour travels to the other end where it is cooled and condenses back to liquid form, releasing the heat it had absorbed.*

***Key Words*: Heat pipe, condensation, evaporation, capillary wicking, thermal conductivity etc.**

1. INTRODUCTION

Heat pipe is also a type of heat exchanger. This pipe is used where the conventional heat exchangers are not used. The origin of this heat pipe is during Second World War. The idea of heat pipe was first suggested by R.S. Gaugler in 1942. In 1964 – G.M. Grover published Research paper and coined name Heat Pipe and invented Heat Pipe. The first heat pipe that Grover built used water as working fluid. On April 5, 1967 the first "zero g" demonstration of a heat pipe was conducted by group of engineers of the Los Alamos Scientific Laboratory. In 1968 RCA developed a heat pipe for transistors used in Aircraft transmitters; this is the first commercial application of Heat pipe. Heat pipes offer high effective thermal conductivities (5,000 W/mK to 200,000 W/mK), energy-efficiency, light weight, low cost and the flexibility of many different size and shape options. As passive heat transfer systems, heat pipes offer simple and reliable operation, with high effective thermal conductivity, no moving parts, ability to transport heat over long distances and quiet vibration-free operation. Heat pipes transfer heat more efficiently and evenly than solid conductors such as aluminium or copper because of their lower total thermal resistance.[1] The heat pipe is filled with a small quantity of working fluid (water, acetone, nitrogen, methanol, ammonia or sodium). Heat is absorbed by vaporizing the working fluid. The vapour transports heat to the condenser region where the condensed vapour releases heat to a cooling medium. The condensed working fluid is returned to the evaporator by gravity, or by the heat pipe's wick structure, creating capillary action [2]. Both cylindrical and planer heat pipe variants have an inner surface lined with a capillary wicking material. This experiment shows effectiveness of heat pipe for heat conduction compared to a metallic rod (Copper in our experiment) by comparing its heat removal rate.

1.1 Structure of Heat Pipe:

It consists of a hollow tube in which annular space is lined with wick structure. The hollow tube is first vacuumed, then charged with working fluid and hermitically sealed. A heat pipe in principle divided into 3 parts they are Evaporator, Adiabatic section, Condenser. The driving force that transports the condensed working liquid through the wick to the evaporator is provided by capillary pressure. Working fluids that are employed in heat pipes have concave facing menisci (wetting liquids) as opposed to convex facing menisci (non-wetting liquids). Contact angle is defined as the angle between the solid and vapour regions. Wetting fluids have angles between 0 and 90 degrees. Non wetting fluids have angles between 90 and 180 degrees.

1.1 Method:

The heat pipe and copper rod should be in the test section in a vertical position, similar to what is shown in the figure. Three K- type thermocouples are placed at different locations on the periphery for both heat pipe and copper rod. These will be used to measure the rod surface temperatures. Place a beaker with water under test section such that 80% of evaporator section of the heat pipe as well as the bottom of the copper rod is in the water. Place the water beaker on a plate heater as shown in the figure. Orifice plates are used mainly incorporated for measuring air flow rate, velocity or Reynolds number.

1.1.1 Capillary Limit:

For a heat pipe to function properly, the capillary pressure must be greater or equal to the sum of the pressure drops due to inertial, viscous, and hydrostatic forces, as well as, pressure gradients. If it is not, then the working fluid is not supplied rapidly enough to the evaporator to compensate for the liquid loss through vaporization. If this occurs, there is dry out in the evaporator.

1.1.2 Wetting angle:

Wetting fluids have a cosθ value that will be positive. This results in a positive capillary pressure that creates a pushing force on the liquid in the wick near the condenser; this forces the liquid to move to the evaporator. Non-wetting fluids will have cosθ values that are negative, resulting in a negative capillary pressure that creates a suction force on the liquid in the wick. The liquid is prevented from moving to the evaporator. For this reason, the working liquid in heat pipes must be a wetting liquid.

2. DESIGN OF HEAT PIPE

Fabrication of 6 inch heat pipe without wick:

The fabrication of a 6 inch heat pipe involves several processes. Initially we took two pipes which are of length 6.5 inch hallow copper pipe and we made end caps for these pipes and end cap length is 0.7 inch. The diameters of these pipes are ½ inch. Then we cleaned these pipes in 3% HNO_3 solution for 30 minutes. After cleaning in 3% HNO_3 solution, we soaked these pipes in hot distilled water which is at 800 C for almost 30 minutes. After this cleaning process we fitted the end cap with copper pipe at one end. In brazing process actually we used copper strings for brazing that end cap and copper pipe as shown in figure.

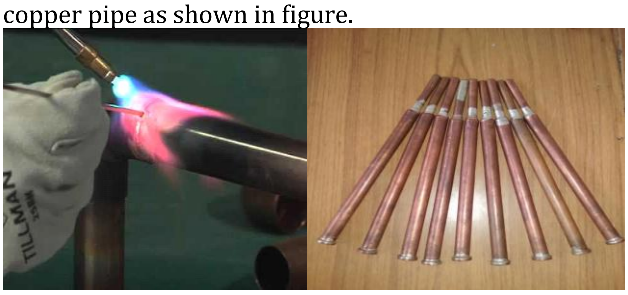

Fig -1: a) Brazing process b) Before pinching

After completion of this brazing process we cleaned these pipes again with 3% HNO3 solution and hot distilled water. After this process we calculated amount of water required for 2 inch condenser length. We poured some excess amount of distilled water and we heated it for some time at constant heat. Then after knowing that steam is coming out we closed the other end of pipe by using pinching equipment as shown in figure.

Fig -2: Pinching equipment b) after pinched copper tube

2.1 Design and Manufacturing of Fins:

A long aluminum sheet of 1 mm thickness is taken and is cuts into 90x90mm length; ten holes are made on the sheet with 1/2 inch diameter length to fit the heat pipes. These holes are made in an accurate manner at an equal length as shown in fig.

Fig -3: a) Aluminum fin sheet b) Ceramic wool

2.1.1 IMPORTANCE OF CERAMIC WOOL:

The Ceramic wool is made up of long cerachem fibers of alumina and silica constituents and zircon. It is an insulating material made from fibres of glass arranged using a binder into a texture similar to wool. The process traps many small pockets of air between the glass, and these small air pockets result in the thermal insulation properties. Thermal insulation with HTIW enabled a more lightweight construction of industrial furnaces and other technical equipment (heating systems, automobiles), resulting in many economic and ecological benefits. Consequences are smaller wall thicknesses and considerably lower lining masses. Wool is produced in rolls or in slabs, with different thermal and mechanical properties. It may also be produced as a material that can be sprayed or applied in place, on the surface to be insulated. Gases possess poor thermal conduction properties compared to liquids, solids. Thus makes a good insulation material if they can be trapped. In order to further augment the effectiveness of a gas (such as air) it may be disrupted into small cells which cannot effectively transfer heat by natural convection.

2.1.2 How a Heat Pipe Works:

A heat pipe is a closed evaporator-condenser system consisting of a sealed, hollow tube whose inside walls are lined with a capillary structure or wick. Thermodynamic working fluid, with substantial vapour pressure at the desired operating temperature, saturates the pores of the wick in a state of equilibrium between liquid and vapour. When heat is applied to the heat pipe, the liquid in the wick heats and evaporates. As the evaporating fluid fills the heat pipe hollow centre, it diffuses throughout its length. Condensation of the vapour occurs wherever the temperature is even slightly below that of the evaporation area. As it condenses, the vapour gives up the heat it acquired during evaporation. This effective high thermal conductance helps maintain near constant temperatures along the entire length of the pipe. Attaching a heat sink to a portion of the heat pipe makes condensation take place at this point of heat transfer and establishes a vapour flow pattern. Capillary action within the wick returns the condensate to the evaporator (heat source) and completes the operating cycle. This system, proven in aerospace applications, transmits thermal energy at rates hundreds of times greater and with a far superior energy-to-weight ratio than can be gained from the most efficient solid conductor.

2.1.3 Thermodynamic Cycle:

1-2 Heat applied to evaporator through external sources vaporizes working fluid to a saturated (2') or superheated (2) vapour. 2-3 Vapour pressure drives vapour through adiabatic section to condenser. 3-4 Vapour condenses, releasing heat to a heat sink. 4-1 Capillary pressure created by menisci in wick pumps condensed fluid into evaporator section Process starts over and Thermodynamic cycle as shown in fig.

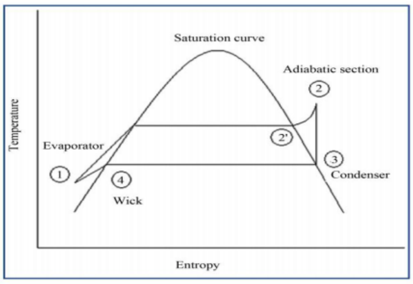

Fig -4: Thermodynamic cycle

2.1.4 Working Fluid:

Heat pipes work on a cycle of vaporization and condensation of the working fluid, which results in the heat pipe's high thermal conductivity. When choosing a working fluid for a heat pipe, the fluid must be able to operate within the heat pipe's operating temperature range. For instance, if the operating temperatures are too high, the fluid may not be able to condense. However, if the operating temperatures are too low the fluid will not be able to evaporate. Watch the saturation temperature for your desired fluid at the desired heat pipe internal pressure. In addition, the working fluid must be compatible with the wick and container material. Operating temperature ranges for various working fluids and Working fluid/ material compatibility as shown below tables 1 & 2

Table -1: Sample Table format

MEDIUM	MELTING PT. (°C)	BOILING PT. AT ATM. PRESSURE (°C)	USEFUL RANGE (°C)
Helium	- 271	- 261	-271 to -269
Nitrogen	- 210	- 196	-203 to -160
Ammonia	- 78	- 33	-60 to 100
Acetone	- 95	57	0 to 120
Methanol	- 98	64	10 to 130
Flutec PP2	- 50	76	10 to 160
Ethanol	- 112	78	0 to 130
Water	0	100	30 to 200
Toluene	- 95	110	50 to 200
Mercury	- 39	361	250 to 650
Sodium	98	892	600 to 1200
Lithium	179	1340	1000 to 1800
Silver	960	2212	1800 to 2300

Table -2: Working fluid/ material compatibility

Working Fluid	Compatible Material	Incompatible Material
Water	Stainless Steel, Copper, Silica, Nickel, Titanium	Aluminium, Inconel
Ammonia	Aluminium, Stainless steel, Nickel	Copper
Methanol	Stainless Steel, Copper, Brass, Silica, Nickel	Aluminium
Acetone	Aluminium, Stainless Steel, Copper, Brass, Silica	Aluminium
Mercury	Stainless Steel	Molybdenum, Nickel, Titanium
Lead	Tungsten, Tantalum	Stainless Steel, nickel
Silver	Tungsten, Tantalum	Rhenium

1. Design of Waste Heat Recovery System:

A hard aluminium sheet of 4mm thickness was considered and it is bent and made into a 90x90mm rectangular cylinder hollow casing of 9inches length. And it is aluminium brazed at one end to get a shape of rectangle. And holes of length 2 inches are done at bottom and top of the rectangular cylinder casing on either side. An extension pipe is drawn out from holes forgiving the inputs of hot and cold air through hot gun and blower respectively as shown in figure. It is completely closed at the bottom end. An opening lid is arranged on the top to insert and remove the pipe-fin arrangement. The adiabatic section is fully insulated by using the ceramic wool. And also the gaps are also insulated by using the ceramic wool where ever necessary, and the final setup fig as shown in below.

Fig -5: heat recovery system setup.

3.1 Experimental results and discussions:

A series of tests was performed in order to investigate the characteristics of the heat pipe heat exchanger, by blowing warm and cool air with constant mass flow rate over the heat pipe heat exchanger. The tests were carried out in the temperature range 100 to 1600C.

The rate of axial heat transfer by conduction of individual heat pipe was calculated and found to be negligible in comparison with heat transport to air. With reference to mass flow rate of warm and cool air, the heat transfer rates to the evaporator and condenser sections are calculated.

The results indicate that temperature difference between the evaporator and condenser sections in 2-3 degrees for a typical 12.5mm outer diameter and 150mm long heat pipe .Whereas the same length copper pipe the Δt was observed to be 20-24 degree.
We have fabricated a heat recovery assembly using 10 heat pies. The performance was evaluated over a temperature of 100 deg to 150 deg. The results show that the heat recovery efficiency can be as high as 35%. In the above graph actually the heat recovered theoretically for ten pipes is almost 2800watts at 1500C. Practically the heat recovered from 10 heat pipes by using 10 fins at 150 0C is almost about 1767watts and efficiency obtained is 62%. The heat recovered from 10 heat pipes by using 20 fins at 1500C is almost about 1740 watts and efficiency obtained is 61.59%.

The heat recovered from 10 heat pipes by using 30 fins at 1500C is almost about 1099watts and efficiency obtained is 38.90%.

Table -3: Heat recovery Performance of a 10 heat pipe

1*	2*	3*	4*	5*	6*	7*	8*
100	2468	580			23.5 008 1		
110	2520	664	132 8	142 0	26.3 492 1	52. 698 41	56.34 921
120	2687	824	137 4	144 8	30.6 661 7	51. 135 09	53.88 91
140	2820	103 1	158 0	163 6	36.5 602 8	56. 028 37	58.01 418
150	2825	109 9	174 0	176 7	38.9 026 5	61. 592 92	62.54 867

1*- Operating temperature ^{0}C, 2*- Theoretical Capacity Of heat pipe
3*- Heat recovered For 30 fins in watts
4* Heat recovered For 20 fins in watts
5*- Heat recovered For 10 fins in watts
6*- Efficiency for 30 fins in %
7*- Efficiency for 20 fins in %
8*- Efficiency for 10 fins in %

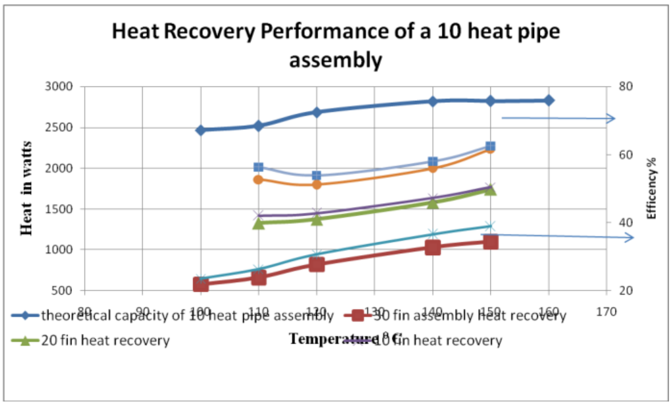

Chart -1: Heat Recovery Performance of a 10 heat pipe assembly

Practical data for 6 inch wick less half inch pipe:

Table 3- Practical data for 6 inch pipe

Length	Water bath temperature in ⁰C	ΔT in ⁰C	Qmaxin Watts
6 inch	60	4	59.4
6 inch	70	3	65.8
6 inch	80	2	69.1

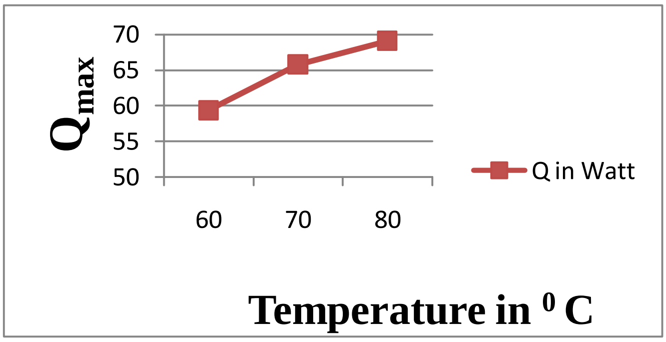

Chart -2: data for 6 inch pipe

The following tables show us the difference between the heat pipe and normal copper rod.

Table 4- Comparison between heat pipe and copper rod:

Heat pipe	ΔT in ⁰C	Copper rod	ΔT in ⁰C	Operating temperature in ⁰C
6 inch	4	6 inch	16	60
6 inch	3	6 inch	17	70
6 inch	2	6 inch	22	80

Table 5- Comparison of theoretical heat pipe and practical heat pipe:

Operating temperature ⁰C	60	70	80
Length In inches	6	6	6
ΔTth in ⁰C	0	0	0
ΔTre in ⁰C	4	3	2
Qth in Watt	60.2	66.76	70
Qre in Watt	59.4	65.8	69.1

2. Model calculation:

Heat recovery performance of 10 heat pipe assembly

Blower Flow rate =1.25 m3/min,

mass =blow rate * density

= (1.25/60)*1.1 (m3/s*kg/m3)

= 0.02291kg/s

$(Q_{max})_{act} = mc_p\Delta T$

$(Q_{max})_{act} = 0.02291*1*70*1000$ Watts

=1764.32 watts

Efficiency=actual/theoretical

= 1764.32/2825=62.54%

3. CONCLUSION

The heat transfer rate to the evaporator section of a single heat pipe obtained from the developed computer simulation was very close to the experimental results for the Constructed heat pipe. The examination of the heat transfer limits for the working fluids showed that the minimum heat transfer is well above the required heat transfer rate. The high effectiveness of the heat exchanger was attributed to the high pitch to Diameter ratio of the pipe and by the limiting of fins.

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