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A literature review on Heat Pipe as an exhaust heat recovery system in the IC Engine

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ABSTRACT

Since the inception industrial revolution, a continuous attempt is being made to recover and minimize the waste heat. With the time various waste heat recovery system is developed. In the present research paper an exhaustive review on heat pipe is done. Various aspects and application is described and the view of authors is presented here. Further, the wide application of heat pipe to recover waste heat from the exhaust of IC engine id discussed and salient conclusion is drawn which indicates that, a wide scope is available for further research on heat pipe and especially in the relation of IC engine exhaust heat recovery system.

1. Introduction

A heat pipe is a heat-transfer device that combines the principles of both thermal conductivity and phase transition to efficiently control the transfer of heat among two solid interfaces. A heat pipe is basically a sealed slender tube containing a wick construction lined on the inner surface and a small quantity of fluid such as water at the saturated state. It is composed of three sections: the evaporator section at one end, a condenser section at the other end and the adiabatic section in between them. In the evaporator heat is absorbed and the fluid is vaporized; in a condenser section the vapor is condensed and heat is rejected; and in the adiabatic section the vapor and the liquid phases of the fluid flow in opposite directions through the core and the wick respectively, to complete the cycle with no significant heat transfer between the fluid and the neighboring medium.

At the hot boundary of a heat pipe a liquid get in touch with a thermally conductive solid face turns into a vapor by absorbing heat from that face. The vapor then travels down the heat pipe to the cold boundary and condenses back into a liquid – releasing the latent heat. The liquid then returns to the hot boundary via capillary action, centrifugal force, or gravity, and the cycle repeats. Due to the very high heat transfer coefficients for boiling and condensation, heat pipes are highly effective thermal conductors. The effective thermal conductivity varies with heat pipe length, and can approach 100 kW/m-K for long heat pipes in comparison of 0.4 kW/m-K copper.

For the heat pipe to convey heat, it must contain saturated liquid and its vapor (gas phase). The saturated liquid vaporizes and moves towards the condenser, where it is cooled and turned back to a saturated liquid. In an ordinary heat pipe, the condensed liquid is returned to the evaporator using a wick structure exerting a capillary action on the liquid phase of the working fluid. In heat pipes wick structures used to contain sintered metal powder, screen, and grooved wicks, which enclose a series of grooves parallel to the pipe axis. When the condenser is situated above the evaporator in a gravitational field, gravity can return the liquid. In this case, the heat pipe is a thermo-siphon. Finally, rotating heat pipes make use of centrifugal forces to return liquid from the condenser to the evaporator [1-2].

2. Construction of a heat pipe

The three basic components which is used in the construction of a heat pipe are as follows:[3]

(i) The container or envelope.
(ii) The wick or capillary structure.
(iii) The working fluid.

The most commonly used envelope (and wick)/fluid pairs include: [2]

- Copper envelope/Water working fluid for electronics cooling. This is by far the most common type of heat pipe.
- Copper or Steel envelope/Refrigerant R134a working fluid for energy recovery in to the HVAC systems.
- Aluminum envelope/Ammonia working fluid in Spacecraft Thermal Control.
- Super alloy envelope/Alkali Metal (Cesium, Potassium, Sodium) working fluid for high temperature heat pipes, most commonly used for calibrating primary temperature measurement devices.

Additional pairs consist of stainless steel envelopes among nitrogen, oxygen, neon, hydrogen, or helium working fluids at temperatures below 100 K, copper/methanol heat pipes for electronics cooling when the heat pipe have to operate below the water range, aluminum/ethane heat pipes for spacecraft thermal control in environments when ammonia can freeze, and refractory metal envelope/lithium working fluid for high temperature (above 1050 °C) applications.[3]

Commonly used wick materials are [4];

1. Glass fiber
2. Wire mesh
3. Sintered material
4. Woven cloths

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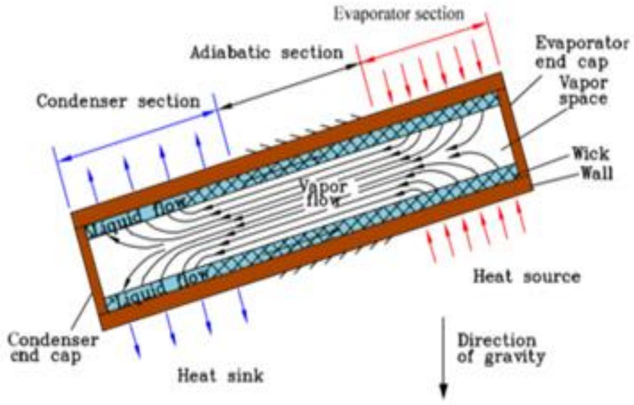

Fig 1. Construction of a heat pipe.

3. The function of heat pipes in heat recovery and energy conservation

In recent times, researchers have created developments of high interest in heat pipe technology for heat recovery. Studies have analyzed the approach, design, construct, thermal performance and application of heat pipes. The use of heat pipes for waste heat recovery is an outstanding way to save energy and prevent global warming. A heat pipe heat exchanger (HPHE) is utilized as an efficient air-to-air heat recovery device in both commercial and industrial applications. The HPHE is the best choice, with almost no cross-leakage between the exhaust gas and supply air. It possesses many advantages, such as its heat recovery effectiveness, compactness, light weight, small pressure drop on the air side, complete separation of hot and cold fluids, relative economy, lack of moving parts, and reliability. The HPHE has been applied extensively in many industries (e.g., energy engineering, chemical engineering and metallurgical engineering) as waste heat recovery systems. One of the most important applications of HPHEs is the recovery of the heat from exhaust gases in a furnace stack. The use a HPHE both reduces the primary energy consumption and protects the environment. still, research on the use of heat pipes for heat recovery, especially with regard to energy savings and environmental benefits, is needed[5].

4. Functions of Heat Pipe in IC Engine

One of the most exciting application of heat pipe in IC Engines is known as VAPIPE. while fitted to a car engine, it appreciably reduces both the fuel utilization and exhaust emission by using heat extracted from exhaust emission by using the heat extracted from exhaust gas for vaporizing petrol mixture from carburetor prior to it enters the engine. The vaporized combination (petrol+ air) makes a homogeneous mixture and improves combustion.

Orr et al [6] reviewed the car waste heat recovery systems and concluded that; two promising technologies that were found to be useful for this purpose were thermoelectric generators (TEGs) and heat pipes. Both TEGs and heat pipes are solid state, passive, silent, scalable and durable. The use of heat pipes can potentially reduce the thermal resistance and pressure losses in the system as well as temperature regulation of the TEGs and increased design flexibility. TEGs do have limitations such as low temperature limits and relatively low efficiency. Heat pipes do have limitations such as maximum rates of heat transfer and temperature limits. When used in conjunction, these technologies have the potential to create a completely solid state and passive waste heat recovery system.

Hongting Ma et. [7] investigated experimentally on heat pipe assisted heat exchanger used for industrial waste heat recovery and analyzing heat transfer rate, heat transfer coefficient, effectiveness, exergy efficiency and number of heat transfer units (NTU). A specially designed on-line cleaning device was used to clean the heat exchange tubes and enhance heat transfer. The results indicated that the exergy efficiency increased with the increment of waste water mass flow rate at constant fresh water mass flow rate, while the effectiveness decreased at the same operation condition. As the waste water mass flow rate varied from 0.83 m^3/h to 1.87 m^3/h, the effectiveness and exergy efficiency varied from 0.19 to 0.09 and from 34% to 41%, respectively. In the present work, the optimal flow rates of waste water and fresh water were 1.20 m^3/h and 3.00 m^3/h, respectively. The on-line cleaning device had an obvious effect on the heat transfer, by performing the device, heat transfer rate, heat transfer coefficient, effectiveness and exergy efficiency were improved by 6.11%, 9.49%, 7.19% and 7.93%, respectively.

Martinez et al. [8] designed a mixed-energy recovery system consisting of two CHPs and indirect evaporative remunerators for the air conditioning. The energy characterization of the mixed energy recovery system was performed with the experimental design techniques. A main conclusion was that by applying the mixed-energy recovery system in the air-air conditioning installations consisting of two CHPs and indirect evaporative systems, part of the energy from the return airflow could be recovered, thus improving the energy efficiency and reducing the environmental impact.

El-Baky and Mohamed [9] investigated the overall effectiveness of utilizing heat pipe heat exchangers for heat recovery through external air-conditioning systems in buildings in order to reduce the cooling load. The thermal performance of the system was analyzed for varying fresh air inlet mass flow rates and temperatures stream. A mathematical model was developed based on the experimental set-up which included the two air ducts of 0.3 m × 0.22 m sectional areas along with the heat pipe arrangement comprising of 25 copper tubes with the evaporator and condenser section of 0.2 m and the adiabatic section of 0.1 m respectively. R-11 was used as a working fluid at a saturation temperature of 303 K. The findings of the study indicated that effectiveness and heat transfer rates are increased with the increase in fresh air inlet temperature. The study also revealed that the mass flow rate ratio has a significant effect of temperature change of fresh air and heat recovery rate is increased by approximately 85% with the increase in fresh air inlet temperature. Yodrak et al. [10] utilized a HPHX air preheater to recover waste heat from the furnace in a hot brass forging process. The HPHX used hot exhaust gas to preheat air which was then sent to the burner of a furnace. The HPHX was designed, constructed, and tested, and a thermal resistance model was developed to predict the rate of heat transfer using the LMTD method. The heat transfer rate was increased with (i) an increase in the inlet gas temperature, (ii) an increase in the HP diameter and (iii) a staggered arrangement of HPs relative to an inline arrangement. The HPHX was shown to reduce furnace fuel consumption by about 20%.

A variety of renewable applications are also available to understand the role of heat pipes to a broader extent. A gas–gas heat pipe heat exchanger consists of a set of similar heat pipes aligned in a tubular arrangement either vertically, horizontally or aligned at an angle.

The evaporation and condensation working principal of the device influences the heat transfer from the countercurrent gas stream which recovers the heat and transports it to the pre-heated air stream. Heat pipe heat exchangers are extremely useful in industrial heat recovery applications due to its static operation and limited auxiliary power requirements along with its entirely reversible process.

Yau and Ahmadzadehtalatapeh [11] reviewed the utility of horizontal pipe heat exchangers as an energy recovery unit in air conditioning systems in tropical climates. The work concluded that the application of horizontal heat pipe heat exchangers for both orientations in terms of dehumidification purposes and energy saving is recommended for tropical climates as a highly efficient heat recovery unit. The work further highlighted the transient simulation of installing double heat pipe heat exchanger units in heating, ventilation and air-conditioning systems for reducing energy consumption rates in tropical climatic behavior.

One of the most widespread commercial uses of heat pipes is associated with solar collectors in order to transfer the direct and diffuse solar radiation to the water stream. Hussein et al. [12] analyzing test work on the comparison of three cross-sectional geometries of wickless heat pipes with varying fill ratios in order to understand the impact of its performance on flat plate solar collectors in Cairo, Egypt. The industrialized group comprised of heat pipe cross-sections which integrated with circular, elliptical and semi-circular arrangement. Experiments were conducted on the group by incorporating the heat pipes into the solar collector array and the comparison results shows that the elliptical design gave a superior performance at 10% water fill ratios with the circular cross-section design proving optimum at 20% water fill ratio respectively.

5. Heat pipe systems

Different types of heat pipes commercially exist, in terms of the method of liquid transport as of the condenser to the evaporator and functionality. This review contain a source of information based on the current published literature on the different types of existing heat pipes which are utilized for a variety of applications requiring moderate to high temperature fluctuations.

5.1. Tubular heat pipes

Conventional tubular heat pipes are the most uncomplicated and accepted type of passive heat transfer devices commercially for use in many global applications for heat transfer over variable distances. The standard set of principle is based on capillary action and the performance is measured in equivalent thermal conductivity. These types of heat pipe can also be used as heat spreaders to isothermal apparatus where homogeneous temperature patterns are chosen.

Liao et al. [13] investigated the thermal performance of a smooth carbon steel-water heat pipe in comparison to its internally finned equivalent. Different influencing parameters including the inclination angle, working temperatures and heat flux formed the basis of the investigation. The experimental set-up comprised of a fiber glass coated carbon steel pipe with a flat band heater for providing heat flux to the evaporator section. The apparatus was placed on an adjustable workbench for alteration of inclination angles and thermocouples were linked to the data logging system for output results. The work revealed that under experimental conditions, the heat transfer coefficient of the internally finned heat pipe was increased by 50–100% in comparison to the smooth heat pipe respectively.

5.2. Variable conductance heat pipes

A variable conductance heat pipe (VCHP) or gas-loaded heat pipe use a Non-Condensable Gas (NCG) to change the heat pipe effective thermal conductivity as power or the heat sink conditions change. It has the ability to sustain a device mounted at the evaporator at a near constant temperature, independent of the amount of power being generated by the device. The most familiar VCHP systems include passive or active feedback-controlled system, both having the capability to control the source of heat at the evaporator end.

Sauciuc et al. [15] analyzed the operation of a VCHP for calculating the temperature of a closed system collection of solar collectors. The experimental set up incorporated a copper/water heat pipe outfitted with a cold reservoir and used air as the Non-Condensable Gas (NCG). The respective thermodynamic properties of water were analyzed and the study was performed at the vapor–NCG interface for various operating pressures. The results shows that the initial point of the VCHP function is considerably based on the amount of NCG content in the heat pipe and on the superheat required for boiling.

5.3. Diodes heat pipe

Fang and Xia [16] calculated the thermal performance of a novel Bidirectional Partition Fluid Thermal Diode (BPFTD) for the function of providing solar heating and passive cooling respectively. The experimental investigation was carried out by testing the BPFTD with two the same hot boxes with similar wall arrangement and comparisons were established with a water-wall of optimum thickness. Test results yielded that the BPFTD had a higher heating performance compared to its water wall counterpart with additional findings confirming an increase in heat supply of around 140% when a single glazing cover without night ventilation is utilized when compared to the water-wall respectively. Varga et al. [17] analyzed tests On the manufactured experimental set-up included nine copper/water bent heat pipes with a diameter of 12.7 mm welded to aluminum sheets along with the thermal diode panels respectively. The thermal and physical properties were tested using a finite element heat transfer model combined with an optimization procedure for both forward and backward heat transfer. To evaluate the performance of thermal diode panels incorporating heat pipes for passive cooling in buildings in Portugal. The work completed the agreement of the applied model with the experimental procedure. Further, the results revealed a significant increase in the forward heat transfer results in comparison to its backward counterpart.

Rhee et al. [18] experimentally investigated the temperature stratification in a solar hot water storage tank. The experiment proposed four different storage tank designs involving thermal diodes for its operation. The results of the test examined that the so-called express-elevator design displayed the highest amount of stratification during both heating and cooling periods in comparison to the other proposed designs. Consequently, the work concluded the bright future scope of optimizing the geometric parameters of thermal diodes to obtain an improved rate of stratification.

5.4. Pulsating heat pipes

A pulsating (oscillating) heat pipe consists of circuitous channel, evacuated and filled with the working fluid. Heat is transferred through the latent heat of vapor and through the sensible heat transferred by the liquid slugs. As the tube on the evaporator section of the heat pipe is put under thermal load, the working fluid evaporates thus increasing the vapor pressure and creation of bubbles and transferring the liquid towards the condenser section where cooling results in a reduction of vapor pressure and condensation of bubbles in the section respectively. The increase and decrease of bubbles in the two sections lead to an oscillating or pulsating motion within the capillary tube.

Qu and Ma [19] investigated the principal factors involved in startup of oscillating motions in a pulsating heat pipe including superheat and heat flux level on the evaporator section and the cavity size on capillary inner surface. The experimental investigation comprised of a glass prototype with a total length of 300 mm and the evaporator section of 90 mm along the constant inlet temperature of 296 K. The results of the theoretical analysis confirmed that the performance at startup can be improved by controlling the vapor bubble type and utilizing a rougher surface. The results also showed that the globe-type vapor bubble needs smaller superheat compared to the taylor type vapor bubble respectively.

Wang et al. [20] studied the thermal performance of heat trans-port of the four-turn pulsating heat pipe by comparing various working fluids with pure water. The experimental analyses were based on two operating orientations (vertical and horizontal) of a copper tube with an external diameter of 2.5 mm. FS-39E microcapsule and Al2O3 nano-fluid were used for the test. The results of the investigation proved that the functional working fluids increase the heat-transport ability of the heat pipe when compared with pure water with the FS-39E microcapsule beingthe best working fluid in the horizontal orientation. Yang et al. [21] carried out work on estimating the thermal performance of closed loop pulsating heat pipes by conducting experiments on copper tubes of varying inner diameters and filling ratios respectively. The system comprised of 40 copper tubes with the inner diameters of 1 mm and 2 mm and the vertical bottom heated, vertical top heated and the horizontal orientations were compared. The investigation findings revealed that the closed loop pulsating heat pipe with the vertical bottom heating gives the best performance with 2 mm inner diameter and 50% fill ratio respectively while the orientation effects were negligible for the 1 mm inner diameter tube.

3.5. Loop heat pipes (LHPs) and capillary pumped loops (CPLs)

The loop heat pipe LHP is based on the same physical processes (evaporation and condensation) as those of conventional heat pipes. The LHP in its simplest form consists of a capillary pump (or evaporator), a compensation chamber (or reservoir), a condenser, and liquid and vapor lines. The wicks are only present in the evaporator and compensation chamber. The high capillary force is created in the evaporator due to fine-pored wicks (primary wicks) such as sintered nickel, titanium and copper powder with an effective pore radius of 0.7-15μm and a porosity of 55-75%. The compensation chamber is an important component in the LHP and is often an integral part of the evaporator. The purpose of the compensation chamber is to accommodate excess liquid in an LHP during normal operation. A secondary wick (usually made of larger pores) physically connects the evaporator to the compensation chamber in order to supply the primary wick with liquid, particularly when the compensation chamber is below the evaporator, or when the LHP is operating in microgravity conditions. The motion of vapor and liquid flow in the primary wick proceeds mainly in a radial direction. The evaporator meniscus is inverted down toward the wall being heated. Both the liquid and vapor lines are made of small diameter tubing with no wicks. LHPs can be made flexible and bendable. LHPs provide heat removal over long distances without sensitivity to gravity.

Loop heat pipes (LHP) employ the characteristics of a conventional heat pipe but have an advantage in terms of its ability to transfer thermal energy over a larger space without any constraint on the path of the liquid or vapor lines and also in terms of a greater heat flux potential and robust operation. For this reason, LHPs are fast becoming typical devices to meet the global demand of control of thermal difficulties of high-end electronics. A capillary force in the evaporator section drives the operation for the LHP requiring no auxiliary power input.

Wang et al. [22] conducted experiments based on a flat LHP under low-heat power input to understand the control of compensation chamber and the evaporator on the start-up behavior. The respective testing system comprised of locating the standard K-type thermocouples, DC stabilized power supply along with an isothermal cooling water tank for experimentation. The results indicated that the LHP has the potential of start-up under low heat power of 6 W. The results also confirmed that the LHP has a better start-up performance under low-power with an increasing thickness of the capillary interlayer.

5.6. Micro heat pipes

Micro heat pipes (MHPs) are used in applications where small to medium heat transfer rates are desirable. The rate of cooling achieved from the MHP is significantly lower compared to forced convection systems. However, the capability to control temperatures in environments of varying heat loads along with its compact size allows it to be utilized in various applications [2].

Hung and Seng [24] carried out work on studying the thermal performance in terms of the heat transport capability of star-groove micro-heat pipes particularity with the influence of the geometrical design. A one-dimensional steady state numerical model was developed to solve the continuity, momentum and energy equations of the liquid and gas phases. The comparison results of the study yielded that the star-groove micro-heat pipe have a better performance characteristic compared to the conventional polygonal micro-heat pipe due to its ability to provide a higher capillary rate by the flexibility in reducing the corner apex angle.

5.7. Sorption heat pipes

Sorption heat pipe (SHP) combines the enhanced heat and mass transfer in conventional heat pipes with sorption phenomena in the sorbent bed. SHP consists of a sorbent system (absorber / desorber and evaporator) at one end and a condenser + evaporator at the other end. It can be used as a cooler/heater and be cooled and heated as a heat pipe. SHP is suggested for space and ground application, because it is insensitive to some "g" acceleration. This device can be composed of a loop heat pipe (LHP), or capillary pumped loop (CPL) and a solid sorption cooler. The most essential feature is that LHP and SHP have the same evaporator, but are working alternatively out of phase. SHP can be applied as a cryogenic cooler, or as a fluid storage canister.

Vasiliev and Vasiliev Jr. [25] conducted an in-depth study on sorption heat pipes as a heat transfer device and highlighted the potential in order to be utilized in cryogenic fluid storage due to its high heat transport ability. The investigation was based on an experimental set-up, comprising of a sorption cooler and a capillary pumped evaporator for both sorption and loop heat pipe arrangement. The results of the experiment revealed that the heat transfer by the sorption heat pipe was in excess of 12 kW/(m^2K), an increase of three times in comparison to a loop heat pipe respectively.

6. Application of heat pipe

1. Electronics- cooling of electronic circuits
2. Electrical motors, generators and transformers
3. Application in HVAC systems
4. Application in IC engines
5. Gas turbine regenerators

6.1 Application to I C Engine (VAPIPE)

One of the most interesting application of heat pipe in IC Engines is known as VAPIPE. When fitted to a car engine, it significantly reduces both the fuel consumption and exhaust emission by using heat extracted from exhaust emission by using the heat extracted from exhaust gas for vaporizing petrol mixture from carburetor before it enters the engine. The vaporized mixture (petrol + air) makes a homogeneous mixture and improves combustion.

Other applications

1. Solar collectors, space applications, snow melting
2. Biscuit and bread ovens
3. Laundries
4. Pharmaceuticals
5. Spray drying
6. Welding booths
7. Brick kilns
8. Plastic lamination drying, extrusion of plastic materials. Temperature uniformity can be maintained in text rising fibers.
9. Annealing furnaces
10. Chemical fluid bed dehumidifier
11. Epoxy coating
12. Curing oven, etc

7. Conclusion

An exhaustive review of paper published in the repute journal indicates that the recovery of waste heat is very important. Recovery and utilization of waste heat has multifaceted view and aspects. At one hand it saves and utilizes energy while other hand it saves the environment. As literature indicates that, there are various heat recovery systems but the heat pipe is in the infant stage. It has various applications including the heat recovery in IC engine. But in spite of all very less research has been done on this heat pipe. Salient conclusion of the present research review on heat pipe indicates that it has ample scope for future research.

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