

EXPERIMENTAL INVESTIGATION ON THE THERMAL PROPERTIES OF VAPOUR CHAMBERS USING NANOCOATING OF TITANIUM OXIDE

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Engineering degree in Mechanical Engineering

By

JEFFI SHARINE C (Reg. No. 39150053)

ARSHEK FARVAIZ H (Reg. No. 39150010)



**DEPARTMENT OF MECHANICAL ENGINEERING
SCHOOL OF MECHANICAL ENGINEERING**

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade "A" by NAAC | 12B Status by UGC | Approved by AICTE

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI - 600119.

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work **JEFFI SHARINE C (39150053)** and **ARSHEK FARVAIZ H(39150010)** who carried out the project entitled **"EXPERIMENTAL INVESTIGATION ON THE THERMAL CHARACTERISTICS OF VAPOUR CHAMBERS USING NANOCOATING OF TITANIUM OXIDE"** under our supervision from June 2022 to May 2023

Project Guide

Dr.V.SRIRAM M.E.,PhD.,

Head of the Department

Dr. G. ARUNKUMAR, M.E., Ph.D.,

Submitted for Viva-voce Examination Held on 10.05.2023

Internal Examiner

External Examiner

DECLARATION

We, **JEFFI SHARINE C** and **ARSHEK FARVAIZ H**, hereby declare that the Project Report entitled **EXPERIMENTAL INVESTIGATION ON THE THERMAL CHARACTERISTICS OF VAPOUR CHAMBERS USING NANOCOATING OF TITANIUM OXIDE** done by under the guidance **Mr. S. VENKATESH., M.E.,(Ph.D.)** at Sathyabama Institute of Science and Technology is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Mechanical Engineering.



DATE:10.05.2023

1) JEFFI SHARINE.C



PLACE: Chennai

2) ARSHEK FARVAIZ.H

SIGNATURE OF THE CANDIDATES

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ABSTRACT

Many industrial applications, adding heat exchangers, air conditioners, fusion reactors, and refrigeration systems, use improved heat transfer surfaces. As a result, numerous techniques have been researched to increase heat transfer rate while reducing the size and cost of the corresponding equipment, particularly in heat exchangers. It is well acknowledged that using heat pipes to collect waste heat is a great approach to conserve energy and stop global warming. Nanomaterials improved surface-to-volume ratio confers greater corrosion prevention characteristics. This review paper helps us to study the corrosion reaction happening in the presence of nanoparticles coating at the top of the surface. When exposed to various corrosive substances and conditions, SS304 exhibits good corrosion resistance. Environments with chlorides can lead to pitting and crevice corrosion. Above 60°C, stress corrosion cracking might happen. Al₂O₃ & TiO₂ are the nanoparticles selected in this project. The key issue of this endeavour is determining whether corrosion occurs when nanoparticles are coated on the heat pipe's surface.

Keywords: heat exchangers, heat transfer rate, waste heat, nanomaterials, corrosion, corrosion prevention.

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LIST OF ABBREVIATIONS

HPHE	HEAT PIPE HEAT EXCHANGE
CHP	COMBINED HEAT AND POWER
TPCT	TWO PHASED CLOSED THERMOSYPHON
OHP	OSCILLATING HEAT PIPE
m.K	MILLIKELVIN
HVAC	HEATING, VENTILATION AND AIR CONDITIONING
CCHP	CONSTANT CONDUCTANCE HEAT PIPE
VCHP	VARIABLE CONDUCTANCE HEAT PIPE
NCG	NON CONDITIONABLE GAS
PCHP	PRESSURE CONTROLLED HEAT PIPES
LHP	LOOP HEAT PIPE

CHAPTER 1

INTRODUCTION

The use of heat pipes for waste heat recovery is a fantastic way to save energy and slow down global warming. An efficient air-to-air heat recovery system is a heat pipe heat exchanger (HPHE), which is utilised in both industrial and in commercial contexts. Because there is nearly no cross-dripping between the air supply and exhaust gas, the HPHE is the best solution. It offers a number of advantages, such as strong heat recovery, a small design, no moving parts, light weight, comparative economy, little air pressure loss, complete separation of cold and hot fluids, reliability, and dependability. As energy recovery heat exchangers, the HPHE has been widely used in a variety of industries, including energy engineering, chemical engineering, and metallurgical engineering. The heat recovery from exhaust gases in a furnace stack is one of the most significant applications for HPHEs. A review was done of the heat recovery applications for the traditional heat pipe (CHP), two-phase closed thermosyphon (TPCT), and oscillating heat pipe (OHP) heat exchangers. The findings of this study add to our knowledge of how to build a heat pipe heat exchanger under ideal conditions and to our understanding of how to proceed with further study in this area.

1.1 Heat pipes:

A heat pipe is a heat-transfer device that employs phase transition to transfer heat between two solid interfaces. At the hot interface of a heat pipe, a volatile liquid in contact with a thermally conductive solid surface turns into a vapor by absorbing heat from that surface. The vapor then travels along the heat pipe to the cold interface and condenses back into a liquid, releasing the latent heat. The liquid then returns to the hot interface through either 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 with approximately 0.4 kW/(m·K) for copper.

1.2 Heat pipe materials and working fluid:

Heat pipes have an envelope, a wick, and a working fluid. Heat pipes are designed

for very long term operation with no maintenance, so the heat pipe wall and wick must be compatible with the working fluid. Some material/working fluids pairs that appear to be compatible are not. For example, water in an aluminium envelope will develop large amounts of non-condensable gas over a few hours or days, preventing normal operation of the heat pipe. Since heat pipes were rediscovered by George Grover in 1963, extensive life tests have been conducted to determine compatible envelope/fluid pairs, some going on for decades. In a heat pipe life test, heat pipes are operated for long periods of time, and monitored for problems such as non-condensable gas generation, material transport, and corrosion.

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

- Copper envelope with water working fluid for electronics cooling. This is by far the most common type of heat pipe.
- Copper or steel envelope with refrigerant R134a working fluid for energy recovery in HVAC systems.
- Aluminium envelope with ammonia working fluid for spacecraft thermal control.
- Superalloy envelope with alkali metal (cesium, potassium, sodium) working fluid for high temperature heat pipes, most commonly used for calibrating primary temperature measurement devices.

Other pairs include stainless steel envelopes with nitrogen, oxygen, neon, hydrogen, or helium working fluids at temperatures below 100 K, copper/methanol heat pipes for electronics cooling when the heat pipe must operate below the water range, aluminium/ethane heat pipes for spacecraft thermal control in environments when ammonia can freeze, and refractory metal envelope/lithium working fluid for high temperature (above 1,050 °C (1,920 °F)) applications.

1.3 Types of heat pipes:

In addition to standard, constant conductance heat pipes (CCHPs), there are a number of other types of heat pipes, including:

- Vapor chambers (planar heat pipes), which are used for heat flux transformation, and isothermalization of surfaces

- Variable conductance heat pipes (VCHPs), which use a Non-Condensable Gas (NCG) to change the heat pipe effective thermal conductivity as power or the heat sink conditions change
- Pressure controlled heat pipes (PCHPs), which are a VCHP where the volume of the reservoir, or the NCG mass can be changed, to give more precise temperature control
- Diode heat pipes, which have a high thermal conductivity in the forward direction, and a low thermal conductivity in the reverse direction
- Thermosyphons, which are heat pipes where the liquid is returned to the evaporator by gravitational/accelerational forces,
- Rotating heat pipes, where the liquid is returned to the evaporator by centrifugal forces

1.3.1 Rotating heat pipes:

Thin planar heat pipes (heat spreaders) have the same primary components as tubular heat pipes: a hermetically sealed hollow vessel, a working fluid, and a closed-loop capillary recirculation system. In addition, an internal support structure or a series of posts are generally used in a vapor chamber to accommodate clamping pressures sometimes up to 90 PSI. This helps prevent collapse of the flat top and bottom when the pressure is applied.

There are two main applications for vapor chambers. First, they are used when high powers and heat fluxes are applied to a relatively small evaporator. Heat input to the evaporator vaporizes liquid, which flows in two dimensions to the condenser surfaces. After the vapor condenses on the condenser surfaces, capillary forces in the wick return the condensate to the evaporator. Note that most vapor chambers are insensitive to gravity, and will still operate when inverted, with the evaporator above the condenser. In this application, the vapor chamber acts as a heat flux transformer, cooling a high heat flux from an electronic chip or laser diode, and transforming it to a lower heat flux that can be removed by natural or forced convection. With special evaporator wicks, vapor chambers can remove 2000 W over 4 cm², or 700 W over 1 cm².

Another major usage of vapor chambers is for cooling purposes in gaming laptops. As vapor chambers are a flatter and more two-dimensional method of heat

dissipation, sleeker gaming laptops benefit hugely from them as compared to traditional heat pipes. For example, the vapor chamber cooling in Lenovo's Legion 7i was its most unique selling point (although it was misadvertised as all models having vapor chambers, while in fact only a few had). Second, compared to a one-dimensional tubular heat pipe, the width of a two-dimensional heat pipe allows an adequate cross section for heat flow even with a very thin device. These thin planar heat pipes are finding their way into "height sensitive" applications, such as notebook computers and surface mount circuit board cores. It is possible to produce flat heat pipes as thin as 1.0 mm (slightly thicker than a 0.76 mm).

1.3.2 Variable conductance heat pipes (VCHPs):

Standard heat pipes are constant conductance devices, where the heat pipe operating temperature is set by the source and sink temperatures, the thermal resistances from the source to the heat pipe, and the thermal resistances from the heat pipe to the sink. In these heat pipes, the temperature drops linearly as the power or condenser temperature is reduced. For some applications, such as satellite or research balloon thermal control, the electronics will be overcooled at low powers, or at the low sink temperatures. Variable Conductance Heat Pipes (VCHPs) are used to passively maintain the temperature of the electronics being cooled as power and sink conditions change.

Variable conductance heat pipes have two additions compared to a standard heat pipe: 1. a reservoir, and 2. a non-condensable gas (NCG) added to the heat pipe, in addition to the working fluid; see the picture in the [spacecraft section below](#). This non-condensable gas is typically argon for standard Variable conductance heat pipes, and helium for thermosyphons. When the heat pipe is not operating, the non-condensable gas and working fluid vapor are mixed throughout the heat pipe vapor space. When the variable conductance heat pipe is operating, the non-condensable gas is swept toward the condenser end of the heat pipe by the flow of the working fluid vapor. Most of the non-condensable gas is located in the reservoir, while the remainder blocks a portion of the heat pipe condenser. The variable conductance heat pipe works by varying the active length of the condenser. When the power or heat sink temperature is increased, the heat pipe vapor temperature and pressure increase. The increased vapor pressure forces more of the non-condensable gas into the reservoir, increasing the active condenser length and the heat pipe

conductance. Conversely, when the power or heat sink temperature is decreased, the heat pipe vapor temperature and pressure decrease, and the non-condensable gas expands, reducing the active condenser length and heat pipe conductance. The addition of a small heater on the reservoir, with the power controlled by the evaporator temperature, will allow thermal control of roughly $\pm 1\text{-}2\text{ }^{\circ}\text{C}$. In one example, the evaporator temperature was maintained in a $\pm 1.65\text{ }^{\circ}\text{C}$ control band, as power was varied from 72 to 150 W, and heat sink temperature varied from $+15\text{ }^{\circ}\text{C}$ to $-65\text{ }^{\circ}\text{C}$. Pressure controlled heat pipes (PCHPs) can be used when tighter temperature control is required. In a pressure controlled heat pipe, the evaporator temperature is used to either vary the reservoir volume, or the amount of non-condensable gas in the heat pipe. Pressure controlled heat pipes have shown milli-Kelvin temperature control.

1.3.3 Diode heat pipes

Conventional heat pipes transfer heat in either direction, from the hotter to the colder end of the heat pipe. Several different heat pipes act as a thermal diode, transferring heat in one direction, while acting as an insulator in the other.

- Thermosyphons, which only transfer heat from the bottom to the top of the thermosyphon, where the condensate returns by gravity. When the thermosyphon is heated at the top, there is no liquid available to evaporate.
- Rotating heat pipes, where the heat pipe is shaped so that liquid can only travel by centrifugal forces from the nominal evaporator to the nominal condenser. Again, no liquid is available when the nominal condenser is heated.
- Vapor trap diode heat pipes.
- Liquid trap diode heat pipes.

A vapor trap diode is fabricated in a similar fashion to a variable conductance heat pipe, with a gas reservoir at the end of the condenser. During fabrication, the heat pipe is charged with the working fluid and a controlled amount of a non-condensable gas (NCG). During normal operation, the flow of the working fluid vapor from the evaporator to the condenser sweeps the non-condensable gas into the reservoir, where it doesn't interfere with the normal heat pipe operation. When the nominal condenser is heated, the vapor flow is from the nominal condenser to the nominal evaporator. The non-condensable gas is dragged along with the flowing vapor,

completely blocking the nominal evaporator, and greatly increasing the thermal resistivity of the heat pipe. In general, there is some heat transfer to the nominal adiabatic section. Heat is then conducted through the heat pipe walls to the evaporator. In one example, a vapor trap diode carried 95 W in the forward direction, and only 4.3 W in the reverse direction.

A liquid trap diode has a wicked reservoir at the evaporator end of the heat pipe, with a separate wick that is not in communication with the wick in the remainder of the heat pipe. During normal operation, the evaporator and reservoir are heated. The vapor flows to the condenser, and liquid returns to the evaporator by capillary forces in the wick. The reservoir eventually dries out, since there is no method for returning liquid. When the nominal condenser is heated, liquid condenses in the evaporator and the reservoir. While the liquid can return to the nominal condenser from the nominal evaporator, the liquid in the reservoir is trapped, since the reservoir wick is not connected. Eventually, all of the liquid is trapped in the reservoir, and the heat pipe ceases operation.

1.3.4 Thermosyphons

Most heat pipes use a wick to return the liquid from the condenser to the evaporator, allowing the heat pipe to operate in any orientation. The liquid is sucked up back to the evaporator by capillary action, similar to the way that a sponge sucks up water when an edge is placed in contact with a pool of water. However the maximum adverse elevation (evaporator over condenser) is relatively small, on the order of 25 cm long for a typical water heat pipe.

If however, the evaporator is located below the condenser, the liquid can drain back by gravity instead of requiring a wick, and the distance between the two can be much longer. Such a gravity aided heat pipe is known as a thermosyphon. In a thermosyphon, liquid working fluid is vaporized by a heat supplied to the evaporator at the bottom of the heat pipe. The vapor travels to the condenser at the top of the heat pipe, where it condenses. The liquid then drains back to the bottom of the heat pipe by gravity, and the cycle repeats. Thermosyphons are diode heat pipes; when heat is applied to the condenser end, there is no condensate available, and hence no way to form vapor and transfer heat to the evaporator.

While a typical terrestrial water heat pipe is less than 30 cm long, thermosyphons are often several meters long. As discussed below, the thermosyphons used to cool the Alaska pipe line were roughly 11 to 12 m long. Even longer thermosyphons have been proposed for the extraction of geothermal energy. For example, Storch et al. fabricated a 53 mm I.D., 92 m long propane thermosyphon that carried roughly 6 kW of heat.

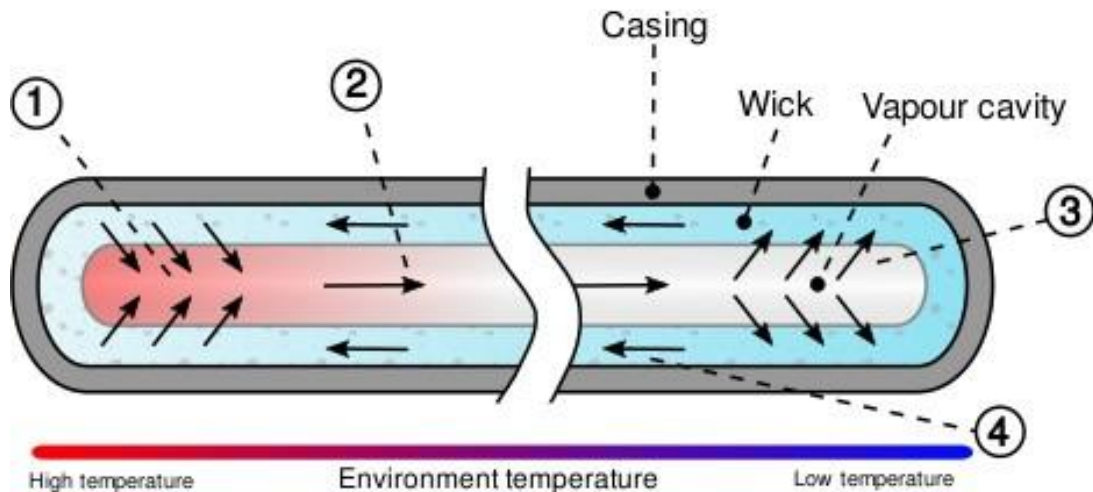


Fig.1.1 Diagram showing components and mechanism for a heat pipe containing a wick

1.3.5 Loop heat pipe

A loop heat pipe (LHP) is a passive two-phase transfer device related to the heat pipe. It can carry higher power over longer distances by having co-current liquid and vapor flow, in contrast to the counter-current flow in a heat pipe. This allows the wick in a loop heat pipe to be required only in the evaporator and compensation chamber. Micro loop heat pipes have been developed and successfully employed in a wide sphere of applications both on the ground and in space.

1.3.6 Oscillating or pulsating heat pipe

An oscillating heat pipe, also known as a pulsating heat pipe, is only partially filled with liquid working fluid. The pipe is arranged in a serpentine pattern in which freely moving liquid and vapor segments alternate. Oscillation takes place in the working fluid; the pipe remains motionless.

1.3.7 Types of heat exchanger pipes:

HPHEs are heat transfer devices that move heat over long distances with a minimal temperature difference by using the latent heat of vaporisation. It is made up of sealed tubes that contain the appropriate operating fluid. Three different forms of heat pipes exist: oscillating heat pipes, two-phase closed thermosyphons, and ordinary heat pipes (OHP). As heat enters the evaporator during operation, the equilibrium is upset, resulting in the production of a vapour with a slightly higher pressure and temperature. In order to condense and release its latent heat of vaporisation at a somewhat lower temperature, the vapour must travel down the pipe at a higher pressure to the condenser section. With the exception of the wick structure, TPCTs are essentially heat pipes. In contrast to a CHP, which uses an air compressor, a TPCT uses gravity to transfer heat from a heat source located below the cold sink. The condenser component is consequently positioned above the absorber component. The working fluid is transported by gravity from the absorber to the condenser, where it evaporates and then condenses. When gravity is an option, TPCTs are chosen over heat pipes since the latter's wicks add an additional obstruction to condensate flow. This illustrates the key difference between the TPCT and the CHP. The pulsating heat pipe, often known as an OHP, is one of the most recent developments in heat pipe technology. The basic heat transfer process in a pulsating heat pipe is the oscillating flow of the fluid connected to a phase transition (evaporation and condensation) processes. The OHP is a collection of twists in a single continuous capillary tube. The diameter of the capillary tube must be sufficiently narrow for the coexistence of the liquid and the vapour plugs. When the working fluid inside the OHP is heated to a very temperature, the vapour pressure is increased, which causes bubbles to develop in the evaporator zone and causes the working fluid to evaporate. As a result, the liquid columns is forced towards to the low temp end (condenser). Condensation at the low temperature end causes the pressure differential between the two ends to increase even further. Since the tubes are connected, the migration of liquid slugs and vapour bubbles from one portion of the tube toward the condenser also causes slugs and bubbles from the next section of the tube to migrate toward the high-temperature end of the tube (the evaporator). The hot area can therefore transfer heat to the chilled portion. The OHP has the advantage that it can transfer fluids without the aid of a wick structure. Due to the

lack of a pump, the OHP is passive. To work, it merely needs the heat being expelled. OHPs use boiling and are not restricted by a boiling limit in addition to the critical temperature flux, therefore even though they typically have higher overall resistance than CHPs, they can operate at larger heat fluxes. The HPHE is a self-contained, self-maintained passive energy recovery device. It has a very high thermal transfer coefficient when using vapor-liquid fluxes. The oscillation of the liquid slugs and bubbles in the OHP is sustained by the condensation of a bubbles in pipes and the evaporation of the liquid slugs. The source of the driving force are the heating of the nucleate and also the condensate of the working fluid. A high-temperature area may be heated by the HPHE and then transferred to a lower-temperature area. Numerous advantages of the OHP include low manufacturing costs, efficient heat transfer, quick temperature response, operability in any location, and operational flexibility. As a mechanism of transporting heat, the working fluid oscillates along the direction of the pipe's longitudinal axis, with bulk circulation occurring simultaneously in both directions. A long capillary tube's ends are joined to form a closed loop to create it. The working fluid can only flow in the appropriate direction thanks to the direction-control one-way control valve that the CLOHP/CVs integrate in the loop. CEOHPs, or closed-end oscillatory heat pipes, are constructed from long capillary tubes that are sealed at both ends. In this case, only oscillations that are fuelled by abrupt, erratic pressure wave disturbances are capable of transferring heat.

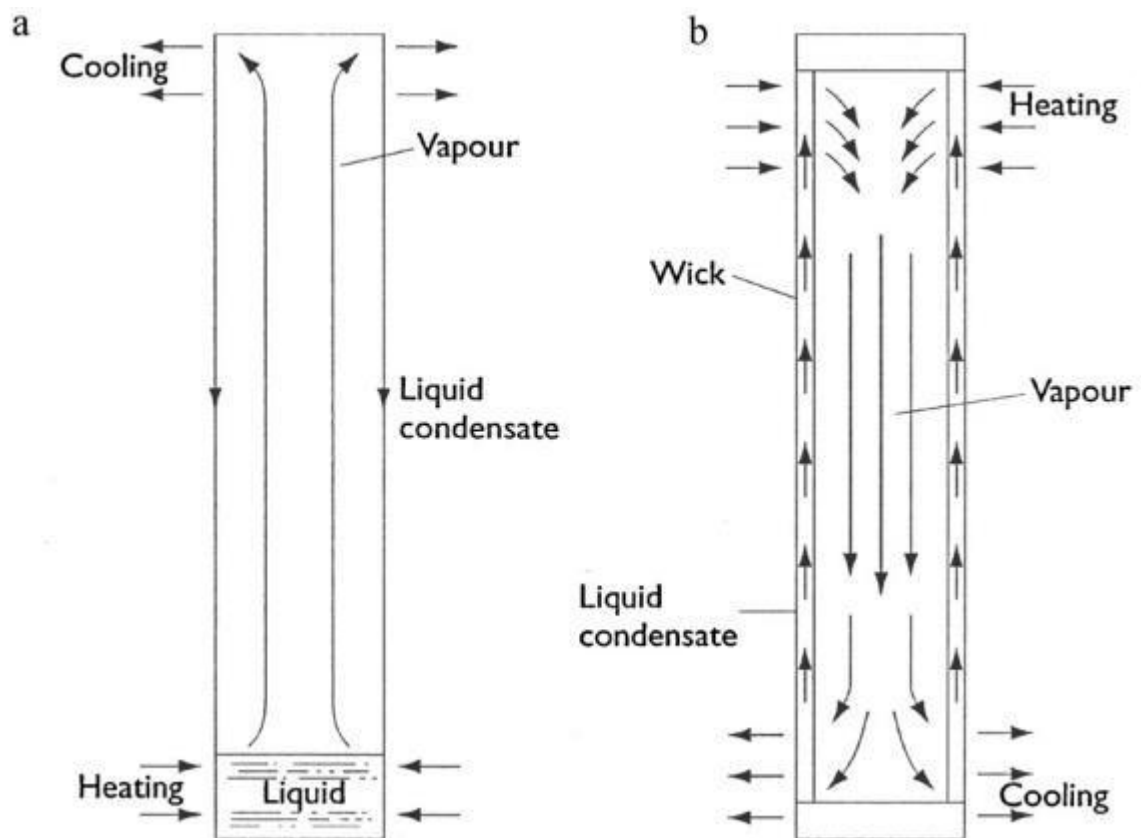


Fig 1.2. Conventional Heat Pipe and Two phased closed thermosiphon.[3]

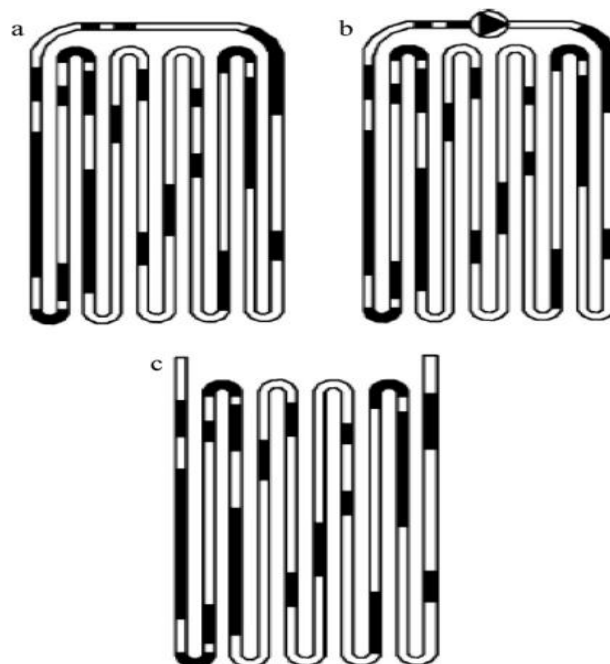


Fig 1.3. Types of Oscillating Heat Pipes

1.3.8 Heat recovery applications of heat pipes:

Recent developments in heat pipe technology for heat recovery have attracted a lot of attention from researchers. Heat pipes' application, manufacture, aesthetics, and thermal performance have all been studied. Noie-Baghban and Majideian's [4] study of waste heat recovery in operating rooms using CHPs in hospitals. The CHPs can use low-temperature sources (15-55 °C). The study showed that CHP efficacy is 0.16, despite variations in diameter and fin spacing. The CHP is relatively small in size because it was designed for low-temperature operating conditions. Abd El-Baky and Mohamed [5] modified CHP for heat recovery between two streams of fresh and return air in an air conditioning system in order to chill the incoming fresh air. The mass flow rate ratios of 1, 1.5, and 2.33 between the return and fresh air were evaluated in order to confirm the heat transfer and temperature change of the fresh air. The trials maintained the fresh air input temperature between 32 and 40 C while maintaining the inlet returned air temperature at around 26 C. The mixed-energy recovering system developed for the air conditioners by Martinez et al. [6] consists of two CHPs and indirect absorber recuperators. The energy characterization of the mixed energy-recovery system was performed out using experimental design approaches. One significant discovery was that the energy from return airflow could be slightly recovered using the blended recovery system in the air to air conditioning facilities consisting of two CHPs and indirect absorber recovery in bakeries, according to Lukitobudi et al. [7]. The experimental results are in good accord with the inevitable feature, and the TPCT was quite efficient (65%), despite the authors' observation that the overload pressure allows TPCTs to be used effectively as a heat recovery device. Riffat and Gan [8] looked at the effectiveness of TPCT heat transfer for naturally ventilated buildings. In this investigation, the performance of three various TPCT heat recovery unit types was assessed in a two-zone chamber with a horizontal barrier. The first TPCT heat exchanger consists of a bank of seven heat pipes with external fins; the second has spine fins with a cylinder shape; and the third is made up of two rows of astonished TPCTs. CFD was used to model the units' pressure loss characteristics. The experimental results showed that the air velocity had a significant influence on the TPCT heat recovery units' efficiency. For the same velocity, the heat recovery efficiency was raised by 16% to 17% by replacing one bank of TPCTs with banks of TPCTs with plain fins. In contrast to staggered pipes' 4.2 and smaller parallel TPCTs' 3.7, a 2-row, parallel design with

six pipes travelling at a speed of 1 m/s had a predicted pressure loss coefficient of 3.3. The study recommended that in naturally ventilated low-rise building structures without the influence of wind, the originally meant mean air velocity should be less than 1 m/s. Wu et al. [9] examined the application of TPCT exchangers for the control of humid in air-conditioning systems in a distinct experiment. Instead of using a conventional reheat coil, this type of heat exchanger can improve the cooling efficiency of the cooling coils while using little to no additional energy. When employing an OHP as a heat exchanger, Rittidech et al. [10] utilised a CEOHP air-preheater for such drying process. The technique used connected the condenser section towards the fresh-air section and the absorber section towards the heat source from gas burner. The dryer-bath arrangement was chosen because the CEOHP air preheater complements it effectively. Heat transmission efficiency and rate were measured, and the outcomes were contrasted with the predicted values. The study found that energy can be saved by using the CEOHP heat exchanger for air preheating in the drying system. To reduce the relative humidity in the drying systems, Meena et al. [11] constructed the CLOHP/CVs for the air preheater in a study quite similar to their own.

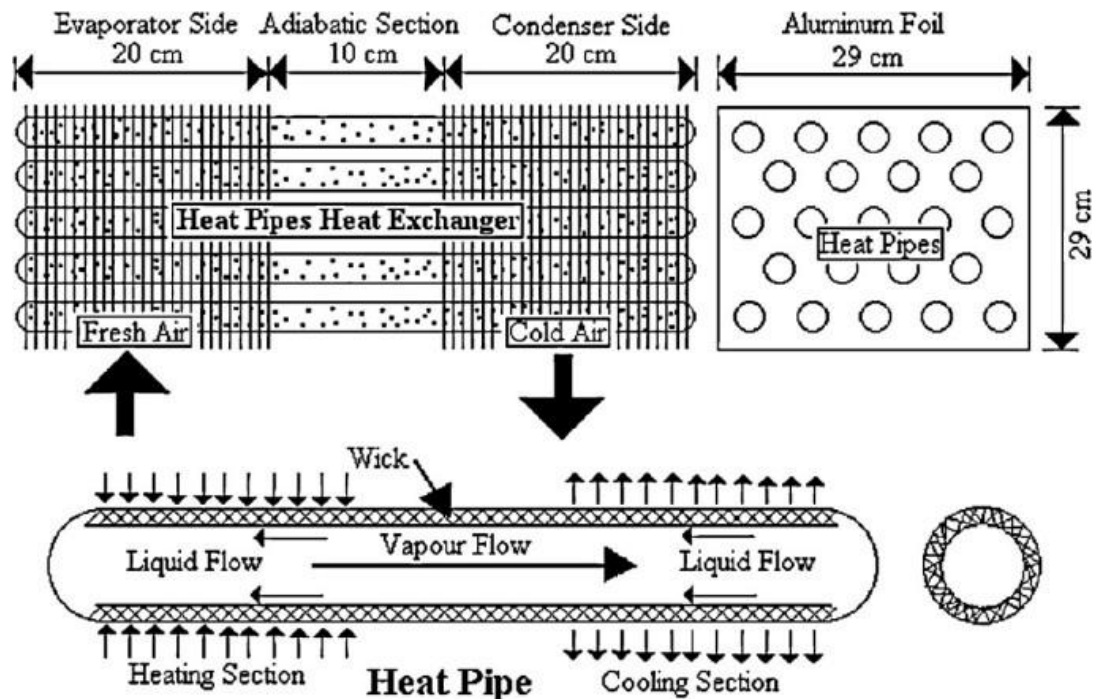


Fig 1.4.CHP heat exchanger for heat recovery

1.4 Heat transfer:

Heat pipes employ phase change to transfer thermal energy from one point to another by the vaporization and condensation of a working fluid or coolant. Heat pipes rely on a temperature difference between the ends of the pipe, and cannot lower temperatures at either end below the ambient temperature (hence they tend to equalize the temperature within the pipe). When one end of the heat pipe is heated, the working fluid inside the pipe at that end vaporizes and increases the vapor pressure inside the cavity of the heat pipe. The latent heat of vaporization absorbed by the working fluid reduces the temperature at the hot end of the pipe. The vapor pressure over the hot liquid working fluid at the hot end of the pipe is higher than the equilibrium vapor pressure over the condensing working fluid at the cooler end of the pipe, and this pressure difference drives a rapid mass transfer to the condensing end where the excess vapor condenses, releases its latent heat, and warms the cool end of the pipe. Non-condensing gases (caused by contamination for instance) in the vapor impede the gas flow and reduce the effectiveness of the heat pipe, particularly at low temperatures, where vapor pressures are low. The speed of molecules in a gas is approximately the speed of sound, and in the absence of noncondensing gases (i.e., if there is only a gas phase present) this is the upper limit to the velocity with which they could travel in the heat pipe. In practice, the speed of the vapor through the heat pipe is limited by the rate of condensation at the cold end and far lower than the molecular speed. Note/explanation: The condensation rate is very close to the sticking coefficient times the molecular speed times the gas density, if the condensing surface is very cold. However, if the surface is close to the temperature of the gas, the evaporation caused by the finite temperature of the surface largely cancels this heat flux. If the temperature difference is more than some tens of degrees, the vaporization from the surface is typically negligible, as can be assessed from the vapor pressure curves. In most cases, with very efficient heat transport through the gas, it is very challenging to maintain such significant temperature differences between the gas and the condensing surface. Moreover, this temperature differences of course corresponds to a large effective thermal resistance by itself. The bottleneck is often less severe at the heat source, as the gas densities are higher there, corresponding to higher maximum heat fluxes.

The condensed working fluid then flows back to the hot end of the pipe. In the case of vertically oriented heat pipes the fluid may be moved by the force of gravity. In the case of heat pipes containing wicks, the fluid is returned by capillary action. When making heat pipes, there is no need to create a vacuum in the pipe. One simply boils the working fluid in the heat pipe until the resulting vapor has purged the non-condensing gases from the pipe, and then seals the end. An interesting property of heat pipes is the temperature range over which they are effective. Initially, it might be suspected that a water-charged heat pipe only works when the hot end reaches the boiling point (100 °C, 212 °F, at normal atmospheric pressure) and steam is transferred to the cold end. However, the boiling point of water depends on the absolute pressure inside the pipe. In an evacuated pipe, water vaporizes from its triple point (0.01 °C, 32 °F) to its critical point (374 °C; 705 °F), as long as the heat pipe contains both liquid and vapor. Thus a heat pipe can operate at hot-end temperatures as low as just slightly warmer than the melting point of the working fluid, although the maximum rate of heat transfer is low at temperatures below 25 °C (77 °F). Similarly, a heat pipe with water as a working fluid can work well above the atmospheric boiling point (100 °C, 212 °F). The maximum temperature for long term water heat pipes is 270 °C (518 °F), with heat pipes operating up to 300 °C (572 °F) for short term tests.

The main reason for the effectiveness of heat pipes is the vaporization and condensation of the working fluid. The heat of vaporization greatly exceeds the specific heat capacity. Using water as an example, the energy needed to evaporate one gram of water is 540 times the amount of energy needed to raise the temperature of that same one gram of water by 1 °C. Almost all of that energy is rapidly transferred to the "cold" end when the fluid condenses there, making a very effective heat transfer system with no moving parts

1.5 Application:

1.5.1 Spacecraft:

Heat pipes on spacecraft typically use a grooved aluminium extrusion as the envelope. Typical grooved aluminium-ammonia VCHP for spacecraft thermal control, with the evaporator section on the bottom, and the non-condensable gas reservoir just below the valve. The spacecraft thermal control system has the function to keep all components on the spacecraft within their acceptable

temperature range. This is complicated by the following:

- Widely varying external conditions, such as eclipses
- Micro-g environment
- Heat removal from the spacecraft by thermal radiation only
- Limited electrical power available, favoring passive solutions
- Long lifetimes, with no possibility of maintenance

Some spacecraft are designed to last for 20 years, so heat transport without electrical power or moving parts is desirable. Rejecting the heat by thermal radiation means that large radiator panes (multiple square meters) are required. Heat pipes and loop heat pipes are used extensively in spacecraft, since they don't require any power to operate, operate nearly isothermally, and can transport heat over long distances.

Grooved wicks are used in spacecraft heat pipes, as shown in the first photograph in this section. The heat pipes are formed by extruding aluminium, and typically have an integral flange to increase the heat transfer area, which lowers the temperature drop. Grooved wicks are used in spacecraft, instead of the screen or sintered wicks used for terrestrial heat pipes, since the heat pipes don't have to operate against gravity in space. This allows spacecraft heat pipes to be several meters long, in contrast to the roughly 25 cm maximum length for a water heat pipe operating on Earth. Ammonia is the most common working fluid for spacecraft heat pipes. Ethane is used when the heat pipe must operate at temperatures below the ammonia freezing temperature.

The second figure shows a typical grooved aluminium/ammonia variable conductance heat pipe (VCHP) for spacecraft thermal control. The heat pipe is an aluminium extrusion, similar to that shown in the first figure. The bottom flanged area is the evaporator. Above the evaporator, the flange is machined off to allow the adiabatic section to be bent. The condenser is shown above the adiabatic section. The non-condensable gas (NCG) reservoir is located above the main heat pipe. The valve is removed after filling and sealing the heat pipe. When electric heaters are used on the reservoir, the evaporator temperature can be controlled within ± 2 K of the setpoint.

1.5.2 Solar thermal:

Heat pipes are also widely used in solar thermal water heating applications in combination with evacuated tube solar collector arrays. In these applications, distilled water is commonly used as the heat transfer fluid inside a sealed length of copper tubing that is located within an evacuated glass tube and oriented towards the sun. In connecting pipes, the heat transport occurs in the liquid steam phase because the thermal transfer medium is converted into steam in a large section of the collecting pipeline.

In solar thermal water heating applications, an individual absorber tube of an evacuated tube collector is up to 40% more efficient compared to more traditional "flat plate" solar water collectors. This is largely due to the vacuum that exists within the tube, which slows down convective and conductive heat loss. Relative efficiencies of the evacuated tube system are reduced however, when compared to flat plate collectors because the latter have a larger aperture size and can absorb more solar energy per unit area. This means that while an individual evacuated tube has better insulation (lower conductive and convective losses) due to the vacuum created inside the tube, an array of tubes found in a completed solar assembly absorbs less energy per unit area due to there being less absorber surface area pointed toward the sun because of the rounded design of an evacuated tube collector. Therefore, real world efficiencies of both designs are about the same.

Evacuated tube collectors reduce the need for anti-freeze additives since the vacuum helps slow heat loss. However, under prolonged exposure to freezing temperatures the heat transfer fluid can still freeze and precautions must be taken to ensure that the freezing liquid does not damage the evacuated tube when designing systems for such environments. Properly designed solar thermal water heaters can be frost protected down to more than -3 °C with special additives and are being used in Antarctica to heat water.

1.6 Corrosion:

Corrosion is a natural process that converts a refined metal into a more chemically stable oxide. It is the gradual deterioration of materials (usually a metal) by chemical or electrochemical reaction with their environment. Corrosion engineering is the field dedicated to controlling and preventing corrosion. In the most common use of the

word, this means electrochemical oxidation of metal in reaction with an oxidant such as oxygen, hydrogen or hydroxide. Rusting, the formation of iron oxides, is a well-known example of electrochemical corrosion. This type of damage typically produces oxide(s) or salt(s) of the original metal and results in a distinctive orange colouration. Corrosion can also occur in materials other than metals, such as ceramics or polymers, although in this context, the term "degradation" is more common. Corrosion degrades the useful properties of materials and structures including strength, appearance and permeability to liquids and gases. Many structural alloys corrode merely from exposure to moisture in air, but the process can be strongly affected by exposure to certain substances. Corrosion can be concentrated locally to form a pit or crack, or it can extend across a wide area more or less uniformly corroding the surface. Because corrosion is a diffusion-controlled process, it occurs on exposed surfaces. As a result, methods to reduce the activity of the exposed surface, such as passivation and chromate conversion, can increase a material's corrosion resistance. However, some corrosion mechanisms are less visible and less predictable.

The chemistry of corrosion is complex; it can be considered an electrochemical phenomenon. During corrosion at a particular spot on the surface of an object made of iron, oxidation takes place and that spot behaves as an anode. The electrons released at this anodic spot move through the metal and go to another spot on the metal and reduce oxygen at that spot in presence of H^+ (which is believed to be available from carbonic acid (H_2CO_3) formed due to dissolution of carbon dioxide from air into water in moist air condition of atmosphere. Hydrogen ion in water may also be available due to dissolution of other acidic oxides from the atmosphere). This spot behaves as a cathode.

1.7 Galvanic corrosion:

Galvanic corrosion occurs when two different metals have physical or electrical contact with each other and are immersed in a common electrolyte, or when the same metal is exposed to electrolyte with different concentrations. In a galvanic couple, the more active metal (the anode) corrodes at an accelerated rate and the more noble metal (the cathode) corrodes at a slower rate. When immersed separately, each metal corrodes at its own rate. What type of metal(s) to use is readily determined by following the galvanic series. For example, zinc is often used

as a sacrificial anode for steel structures. Galvanic corrosion is of major interest to the marine industry and also anywhere water (containing salts) contacts pipes or metal structures. Factors such as relative size of anode, types of metal, and operating conditions (temperature, humidity, salinity, etc.) affect galvanic corrosion. The surface area ratio of the anode and cathode directly affects the corrosion rates of the materials. Galvanic corrosion is often prevented by the use of sacrificial anodes.

1.7.1 Galvanic series

In any given environment (one standard medium is aerated, room-temperature seawater), one metal will be either more *noble* or more *active* than others, based on how strongly its ions are bound to the surface. Two metals in electrical contact share the same electrons, so that the "tug-of-war" at each surface is analogous to competition for free electrons between the two materials. Using the electrolyte as a host for the flow of ions in the same direction, the noble metal will take electrons from the active one. The resulting mass flow or electric current can be measured to establish a hierarchy of materials in the medium of interest. This hierarchy is called a *galvanic series* and is useful in predicting and understanding corrosion

1.8 Corrosion removal:

Often it is possible to chemically remove the products of corrosion. For example, phosphoric acid in the form of *naval jelly* is often applied to ferrous tools or surfaces to remove rust. Corrosion removal should not be confused with electropolishing, which removes some layers of the underlying metal to make a smooth surface. For example, phosphoric acid may also be used to electropolish copper but it does this by removing copper, not the products of copper corrosion.

1.8.1 Resistance to corrosion:

Some metals are more intrinsically resistant to corrosion than others (for some examples, see galvanic series). There are various ways of protecting metals from corrosion (oxidation) including painting, hot-dip galvanization, cathodic protection, and combinations of these.

1.8.2 Intrinsic chemistry:

The materials most resistant to corrosion are those for which corrosion

is thermodynamically unfavorable. Any corrosion products of gold or platinum tend to decompose spontaneously into pure metal, which is why these elements can be found in metallic form on Earth and have long been valued. More common "base" metals can only be protected by more temporary means.

Some metals have naturally slow reaction kinetics, even though their corrosion is thermodynamically favorable. These include such metals as zinc, magnesium, and cadmium. While corrosion of these metals is continuous and ongoing, it happens at an acceptably slow rate. An extreme example is graphite, which releases large amounts of energy upon oxidation, but has such slow kinetics that it is effectively immune to electrochemical corrosion under normal conditions.

1.8.3 Passivation:

Passivation refers to the spontaneous formation of an ultrathin film of corrosion products, known as a passive film, on the metal's surface that act as a barrier to further oxidation. The chemical composition and microstructure of a passive film are different from the underlying metal. Typical passive film thickness on aluminium, stainless steels, and alloys is within 10 nanometers. The passive film is different from oxide layers that are formed upon heating and are in the micrometer thickness range – the passive film recovers if removed or damaged whereas the oxide layer does not. Passivation in natural environments such as air, water and soil at moderate pH is seen in such materials as aluminium, stainless steel, titanium, and silicon.

Passivation is primarily determined by metallurgical and environmental factors. The effect of pH is summarized using Pourbaix diagrams, but many other factors are influential. Some conditions that inhibit passivation include high pH for aluminium and zinc, low pH or the presence of chloride ions for stainless steel, high temperature for titanium (in which case the oxide dissolves into the metal, rather than the electrolyte) and fluoride ions for silicon. On the other hand, unusual conditions may result in passivation of materials that are normally unprotected, as the alkaline environment of concrete does for steel rebar. Exposure to a liquid metal such as mercury or hot solder can often circumvent passivation mechanisms.

1.9 Corrosion in passivated material:

Passivation is extremely useful in mitigating corrosion damage, however even a

high-quality alloy will corrode if its ability to form a passivating film is hindered. Proper selection of the right grade of material for the specific environment is important for the long-lasting performance of this group of materials. If breakdown occurs in the passive film due to chemical or mechanical factors, the resulting major modes of corrosion may include pitting corrosion, crevice corrosion, and stress corrosion cracking.

1.9.1 Pitting corrosion:

Certain conditions, such as low concentrations of oxygen or high concentrations of species such as chloride which compete as anions, can interfere with a given alloy's ability to re-form a passivating film. In the worst case, almost all of the surface will remain protected, but tiny local fluctuations will degrade the oxide film in a few critical points. Corrosion at these points will be greatly amplified, and can cause *corrosion pits* of several types, depending upon conditions. While the corrosion pits only nucleate under fairly extreme circumstances, they can continue to grow even when conditions return to normal, since the interior of a pit is naturally deprived of oxygen and locally the pH decreases to very low values and the corrosion rate increases due to an autocatalytic process. In extreme cases, the sharp tips of extremely long and narrow corrosion pits can cause stress concentration to the point that otherwise tough alloys can shatter; a thin film pierced by an invisibly small hole can hide a thumb sized pit from view. These problems are especially dangerous because they are difficult to detect before a part or structure fails. Pitting remains among the most common and damaging forms of corrosion in passivated alloys, but it can be prevented by control of the alloy's environment.

Pitting results when a small hole, or cavity, forms in the metal, usually as a result of de-passivation of a small area. This area becomes anodic, while part of the remaining metal becomes cathodic, producing a localized galvanic reaction. The deterioration of this small area penetrates the metal and can lead to failure. This form of corrosion is often difficult to detect due to the fact that it is usually relatively small and may be covered and hidden by corrosion-produced compounds.

1.9.2 Weld decay and knifeline attack:

Stainless steel can pose special corrosion challenges, since its passivating behavior relies on the presence of a major alloying component (chromium, at least 11.5%).

Because of the elevated temperatures of welding and heat treatment, chromium carbides can form in the grain boundaries of stainless alloys. This chemical reaction robs the material of chromium in the zone near the grain boundary, making those areas much less resistant to corrosion. This creates a galvanic couple with the well-protected alloy nearby, which leads to "weld decay" (corrosion of the grain boundaries in the heat affected zones) in highly corrosive environments. This process can seriously reduce the mechanical strength of welded joints over time.

A stainless steel is said to be "sensitized" if chromium carbides are formed in the microstructure. A typical microstructure of a normalized type 304 stainless steel shows no signs of sensitization, while a heavily sensitized steel shows the presence of grain boundary precipitates. The dark lines in the sensitized microstructure are networks of chromium carbides formed along the grain boundaries. Special alloys, either with low carbon content or with added carbon "getters" such as titanium and niobium (in types 321 and 347, respectively), can prevent this effect, but the latter require special heat treatment after welding to prevent the similar phenomenon of "knifeline attack". As its name implies, corrosion is limited to a very narrow zone adjacent to the weld, often only a few micrometers across, making it even less noticeable.

1.9.3 Crevice corrosion:

Crevice corrosion is a localized form of corrosion occurring in confined spaces (crevices), to which the access of the working fluid from the environment is limited. Formation of a differential aeration cell leads to corrosion inside the crevices. Examples of crevices are gaps and contact areas between parts, under gaskets or seals, inside cracks and seams, spaces filled with deposits and under sludge piles. Crevice corrosion is influenced by the crevice type (metal-metal, metal-non-metal), crevice geometry (size, surface finish), and metallurgical and environmental factors. The susceptibility to crevice corrosion can be evaluated with ASTM standard procedures. A critical crevice corrosion temperature is commonly used to rank a material's resistance to crevice corrosion.

1.9.4 Hydrogen grooving:

In the chemical industry, hydrogen grooving is the corrosion of piping by grooves created by the interaction of a corrosive agent, corroded pipe constituents,

and hydrogen gas bubbles.^[4] For example, when sulfuric acid (H_2SO_4) flows through steel pipes, the iron in the steel reacts with the acid to form a passivation coating of iron sulfate (FeSO_4) and hydrogen gas (H_2). The iron sulfate coating will protect the steel from further reaction; however, if hydrogen bubbles contact this coating, it will be removed. Thus, a groove will be formed by a travelling bubble, exposing more steel to the acid: a vicious cycle. The grooving is exacerbated by the tendency of subsequent bubbles to follow the same path.

1.10 High temperature corrosion :

High-temperature corrosion is chemical deterioration of a material (typically a metal) as a result of heating. This non-galvanic form of corrosion can occur when a metal is subjected to a hot atmosphere containing oxygen, sulfur, or other compounds capable of oxidizing (or assisting the oxidation of) the material concerned. For example, materials used in aerospace, power generation and even in car engines have to resist sustained periods at high temperature in which they may be exposed to an atmosphere containing potentially highly corrosive products of combustion.

The products of high-temperature corrosion can potentially be turned to the advantage of the engineer. The formation of oxides on stainless steels, for example, can provide a protective layer preventing further atmospheric attack, allowing for a material to be used for sustained periods at both room and high temperatures in hostile conditions. Such high-temperature corrosion products, in the form of compacted oxide layer glazes, prevent or reduce wear during high-temperature sliding contact of metallic (or metallic and ceramic) surfaces. Thermal oxidation is also commonly used as a route towards the obtainment of controlled oxide nanostructures, including nanowires and thin films.

1.10.1 Metal dusting :

Metal dusting is a catastrophic form of corrosion that occurs when susceptible materials are exposed to environments with high carbon activities, such as synthesis gas and other high-CO environments. The corrosion manifests itself as a break-up of bulk metal to metal powder. The suspected mechanism is firstly the deposition of a graphite layer on the surface of the metal, usually from carbon monoxide (CO) in the vapor phase. This graphite layer is then thought to form metastable M_3C species (where M is the metal), which migrate away from the metal surface. However, in

some regimes no M_3C species is observed indicating a direct transfer of metal atoms into the graphite layer.

1.10.2 Protection from corrosion:

Various treatments are used to slow corrosion damage to metallic objects which are exposed to the weather, salt water, acids, or other hostile environments. Some unprotected metallic alloys are extremely vulnerable to corrosion, such as those used in neodymium magnets, which can spall or crumble into powder even in dry, temperature-stable indoor environments unless properly treated to discourage corrosion.

1.10.3 Surface treatments:

When surface treatments are used to deter corrosion, great care must be taken to ensure complete coverage, without gaps, cracks, or pinhole defects. Small defects can act as an "Achilles' heel", allowing corrosion to penetrate the interior and causing extensive damage even while the outer protective layer remains apparently intact for a period of time. Plating, painting, and the application of enamel are the most common anti-corrosion treatments. They work by providing a barrier of corrosion-resistant material between the damaging environment and the structural material. Aside from cosmetic and manufacturing issues, there may be tradeoffs in mechanical flexibility versus resistance to abrasion and high temperature. Platings usually fail only in small sections, but if the plating is more noble than the substrate (for example, chromium on steel), a galvanic couple will cause any exposed area to corrode much more rapidly than an unplated surface would. For this reason, it is often wise to plate with active metal such as zinc or cadmium. If the zinc coating is not thick enough the surface soon becomes unsightly with rusting obvious. The design life is directly related to the metal coating thickness. Painting either by roller or brush is more desirable for tight spaces; spray would be better for larger coating areas such as steel decks and waterfront applications. Flexible polyurethane coatings, like Durabak-M26 for example, can provide an anti-corrosive seal with a highly durable slip resistant membrane. Painted coatings are relatively easy to apply and have fast drying times although temperature and humidity may cause dry times to vary. Nowadays, organic coatings made using petroleum based polymer are being replaced with many renewable source based

organic coatings. Among various vehicles or binders, polyurethanes are the most explored polymer in such attempts.

1.10.4 Reactive coatings:

If the environment is controlled (especially in recirculating systems), corrosion inhibitors can often be added to it. These chemicals form an electrically insulating or chemically impermeable coating on exposed metal surfaces, to suppress electrochemical reactions. Such methods make the system less sensitive to scratches or defects in the coating, since extra inhibitors can be made available wherever metal becomes exposed. Chemicals that inhibit corrosion include some of the salts in hard water (Roman water systems are famous for their mineral deposits), chromates, phosphates, polyaniline, other conducting polymers and a wide range of specially designed chemicals that resemble surfactants (i.e. long-chain organic molecules with ionic end groups).

1.10.5 Anodization:



Fig 1.5. This climbing descender is anodized with a yellow finish.

Aluminium alloys often undergo a surface treatment. Electrochemical conditions in the bath are carefully adjusted so that uniform pores, several nanometers wide, appear in the metal's oxide film. These pores allow the oxide to grow much thicker than passivating conditions would allow. At the end of the treatment, the pores are allowed to seal, forming a harder-than-usual surface layer. If this coating is scratched, normal passivation processes take over to protect the damaged area.

Anodizing is very resilient to weathering and corrosion, so it is commonly used for building facades and other areas where the surface will come into regular contact with the elements. While being resilient, it must be cleaned frequently. If left without cleaning, panel edge staining will naturally occur. Anodization is the process of converting an anode into cathode by bringing a more active anode in contact with it.

1.10.6 Biofilm coatings:

A new form of protection has been developed by applying certain species of bacterial films to the surface of metals in highly corrosive environments. This process increases the corrosion resistance substantially. Alternatively, antimicrobial-producing biofilms can be used to inhibit mild steel corrosion from sulfate-reducing bacteria.

1.10.7 Controlled permeability formwork:

Controlled permeability formwork (CPF) is a method of preventing the corrosion of reinforcement by naturally enhancing the durability of the cover during concrete placement. CPF has been used in environments to combat the effects of carbonation, chlorides, frost and abrasion.

1.11 Economic impact:

In 2002, the US Federal Highway Administration released a study titled "Corrosion Costs and Preventive Strategies in the United States" on the direct costs associated with metallic corrosion in the US industry. In 1998, the total annual direct cost of corrosion in the U.S. was ca. \$276 billion (ca. 3.2% of the US gross domestic product).^[10] Broken down into five specific industries, the economic losses are \$22.6 billion in infrastructure; \$17.6 billion in production and manufacturing; \$29.7 billion in transportation; \$20.1 billion in government; and \$47.9 billion in utilities. Rust is one of the most common causes of bridge accidents. As rust has a much higher volume than the originating mass of iron, its build-up can also cause failure by

forcing apart adjacent parts. It was the cause of the collapse of the Mianus River Bridge in 1983, when the bearings rusted internally and pushed one corner of the road slab off its support. Three drivers on the roadway at the time died as the slab fell into the river below. The following NTSB investigation showed that a drain in the road had been blocked for road re-surfacing, and had not been unblocked; as a result, runoff water penetrated the support hangers. Rust was also an important factor in the Silver Bridge disaster of 1967 in West Virginia, when a steel suspension bridge collapsed within a minute, killing 46 drivers and passengers on the bridge at the time.



Fig 1.6. The collapsed Silver Bridge

Similarly, corrosion of concrete-covered steel and iron can cause the concrete to spall, creating severe structural problems. It is one of the most common failure modes of reinforced concrete bridges. Measuring instruments based on the half-cell potential can detect the potential corrosion spots before total failure of the concrete

structure is reached. Until 20–30 years ago, galvanized steel pipe was used extensively in the potable water systems for single and multi-family residents as well as commercial and public construction. Today, these systems have long ago consumed the protective zinc and are corroding internally resulting in poor water quality and pipe failures. The economic impact on homeowners, condo dwellers, and the public infrastructure is estimated at 22 billion dollars as the insurance industry braces for a wave of claims due to pipe failures.

1.12 Corrosion in non-metals:

Most ceramic materials are almost entirely immune to corrosion. The strong chemical bonds that hold them together leave very little free chemical energy in the structure; they can be thought of as already corroded. When corrosion does occur, it is almost always a simple dissolution of the material or chemical reaction, rather than an electrochemical process. A common example of corrosion protection in ceramics is the lime added to soda-lime glass to reduce its solubility in water; though it is not nearly as soluble as pure sodium silicate, normal glass does form sub-microscopic flaws when exposed to moisture. Due to its brittleness, such flaws cause a dramatic reduction in the strength of a glass object during its first few hours at room temperature.

1.12.1 Corrosion of polymers:

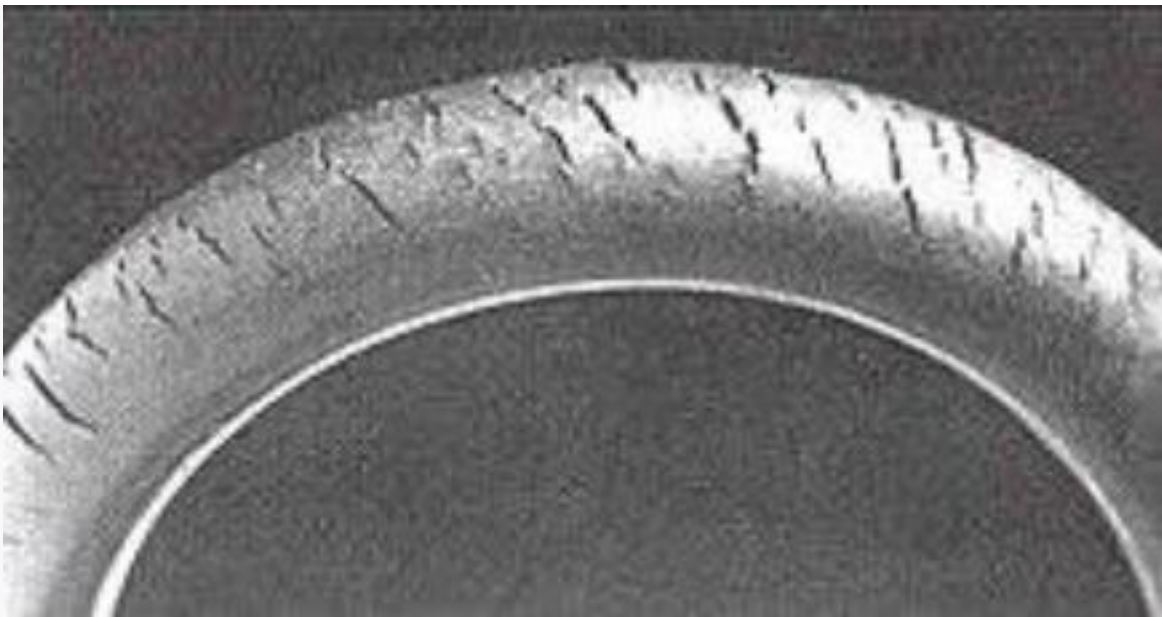


Fig 1.7. Ozone cracking in natural rubber tubing

Polymer degradation involves several complex and often poorly understood physiochemical processes. These are strikingly different from the other processes discussed here, and so the term "corrosion" is only applied to them in a loose sense of the word. Because of their large molecular weight, very little entropy can be gained by mixing a given mass of polymer with another substance, making them generally quite difficult to dissolve. While dissolution is a problem in some polymer applications, it is relatively simple to design against. A more common and related problem is "swelling", where small molecules infiltrate the structure, reducing strength and stiffness and causing a volume change. Conversely, many polymers (notably flexible vinyl) are intentionally swelled with plasticizers, which can be leached out of the structure, causing brittleness or other undesirable changes. The most common form of degradation, however, is a decrease in polymer chain length. Mechanisms which break polymer chains are familiar to biologists because of their effect on DNA: ionizing radiation (most commonly ultraviolet light), free radicals, and oxidizers such as oxygen, ozone, and chlorine. Ozone cracking is a well-known problem affecting natural rubber for example. Plastic additives can slow these process very effectively, and can be as simple as a UV-absorbing pigment (e.g. titanium dioxide or carbon black). Plastic shopping bags often do not include these additives so that they break down more easily as ultrafine particles of litter.

1.12.2 Corrosion of glass



Fig 1.8. Glass corrosion

Glass is characterized by a high degree of corrosion-resistance. Because of its high water-resistance it is often used as primary packaging material in the pharma industry since most medicines are preserved in a watery solution. Besides its water-

resistance, glass is also robust when exposed to certain chemically aggressive liquids or gases. Glass disease is the corrosion of silicate glasses in aqueous solutions. It is governed by two mechanisms: diffusion-controlled leaching (ion exchange) and hydrolytic dissolution of the glass network. Both mechanisms strongly depend on the pH of contacting solution: the rate of ion exchange decreases with pH as $10^{-0.5\text{pH}}$ whereas the rate of hydrolytic dissolution increases with pH as $10^{0.5\text{pH}}$. Mathematically, corrosion rates of glasses are characterized by normalized corrosion rates of elements NR_i ($\text{g}/\text{cm}^2\cdot\text{d}$) which are determined as the ratio of total amount of released species into the water M_i (g) to the water-contacting surface area S (cm^2), time of contact t (days) and weight fraction content of the element in the glass.

1.13 Glass corrosion tests:

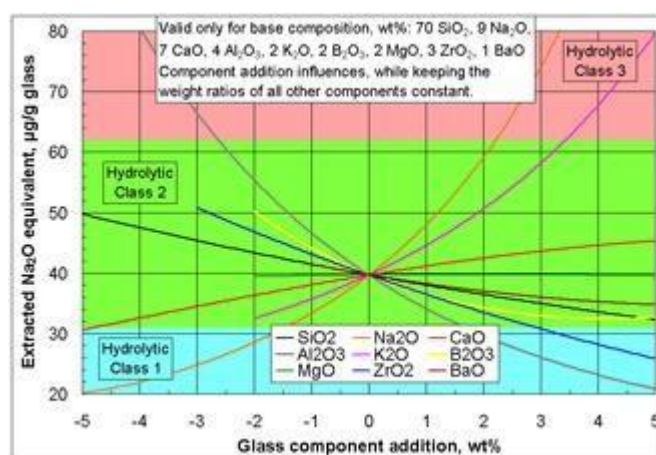


Fig 1.9. Effect of addition of a certain glass component on the chemical durability against water corrosion of a specific base glass (corrosion test ISO 719).

There exist numerous standardized procedures for measuring the corrosion (also called **chemical durability**) of glasses in neutral, basic, and acidic environments, under simulated environmental conditions, in simulated body fluid, at high temperature and pressure, and under other conditions. The standard procedure ISO 719 describes a test of the extraction of water-soluble basic compounds under neutral conditions: 2 g of glass, particle size 300–500 μm , is kept for 60 min in 50 mL de-ionized water of grade 2 at 98 °C; 25 mL of the obtained solution is titrated against 0.01 mol/L HCl solution.

The volume of HCl required for neutralization is classified according to the table below.

Amount of 0.01M HCl needed to neutralize extracted basic oxides, mL	Extracted Na_2O equivalent, μg	Hydrolytic class
< 0.1	< 31	1
0.1-0.2	31-62	2
0.2-0.85	62-264	3
0.85-2.0	264-620	4
2.0-3.5	620-1085	5
> 3.5	> 1085	> 5

Table 1. Table for Glass corrosion

The standardized test ISO 719 is not suitable for glasses with poor or not extractable alkaline components, but which are still attacked by water, e.g. quartz glass, B_2O_3 glass or P_2O_5 glass.

Usual glasses are differentiated into the following classes:

1.13.1.1 Hydrolytic class 1 (Type I):

This class, which is also called neutral glass, includes borosilicate glasses (e.g. Duran, Pyrex, Fiolax). Glass of this class contains essential quantities of boron oxides, aluminium oxides and alkaline earth oxides. Through its composition neutral glass has a high resistance against temperature shocks and the highest hydrolytic resistance. Against acid and neutral solutions it shows high chemical resistance, because of its poor alkali content against alkaline solutions.

1.13.2 Hydrolytic class 2 (Type II):

This class usually contains sodium silicate glasses with a high hydrolytic resistance through surface finishing. Sodium silicate glass is a silicate glass, which contains alkali- and alkaline earth oxide and primarily sodium oxide and Calcium oxide.

1.13.3 Hydrolytic class 3 (Type III):

Glass of the 3rd hydrolytic class usually contains sodium silicate glasses and has a mean hydrolytic resistance, which is two times poorer than of type 1 glasses. Acid class DIN 12116 and alkali class DIN 52322 (ISO 695) are to be distinguished from the hydrolytic class DIN 12111 (ISO 719).

CHAPTER 2

LITERATURE SURVEY

Hamid Ghorabae et al., This paper helps us to understand the mechanisms of heat transfer when nanofluid are used in thermosiphon heat pipe. this paper helps us to understand the influence of heat input, type and concentration of nanoparticles on the thermal behavior of Thermosiphon heat pipes are investigated. Nanofluids significantly improves the thermal characteristics of THP by decreasing the thermal resistance and increase the thermal efficiency of THP. The thermal performance of Thermosiphon heat pipes strongly depends on operating variables, especially the type of nanoparticles, their concentration and addition of surfactant and heat inputs. Further, the thermal performance of the Thermosiphon heat pipes at various heat input is remarkably related to the type of nanofluid. This study also presents a review of the application of the nanofluid-based heat pipes in energy systems. Finally, some challenges are identified and suggestions are made to improve the future investigations.

P.Pandiyaraj et al., This paper helps us to understand the thermal performance of fabricated flat plate heat pipe using Titanium Di-Oxide nanofluid. the design for flat plate heat pipe is made for electronic equipment cooling. Many experiments were conducted to ascertain the thermal performance of the fabricated heat pipe and detailed analysis is discussed from the outcomes of this experiment. The FPHP (Flat plate heat pipe) charged with the nanofluid has been tested for thermal performance and found to be improved with the rise in temperature. The condenser section has been tested with two types of cooling arrangements as natural and forced convection. Comparing the results the forced convection experiment are showing extremely good performance. The thermal resistance in forced convection side is reduced considerably upto 80W of power input and showing gradual increase with higher power inputs which is stabilized at 0.25 °C/W.

M.Vijayakumar et al., This paper helps us to understand the experimental investigation is conducted in the heat transfer characteristics of inclined copper sintered wick heat pipes using surfactant free CuO and Al₂O₃ nanofluids. The morphology and size of CuO and Al₂O₃ nanoparticles kept remains same as well as the effects of mass concentration at an optimum inclination angle of 45° is

studied. The addition of nanoparticles in a base fluid reduces the difference between the surface and vapour temperature of heat pipe. The thermal resistance of the heat pipe has showed a decreasing trend with the inclusion of nanoparticles & their concentration. The reduction in thermal resistance is achieved as 20.13%, 49.64% and 28.22%, for CuO nanofluids and 14.55%, 26.07% and 39.67% for Al₂O₃ nanofluids respectively.

R. Ramachandran et al., This paper helps us to understand the thermal performance of a cylindrical screen mesh heat pipe with hybrid nanofluid was experimentally investigated. The nanofluid was prepared by mixing Al₂O₃ and CuO nanoparticles with deionised water. The heat pipe was fabricated with straight copper tube of dimension 300 mm length, 12.5 mm outer diameter and 1mm thickness. The wick structure in the heat pipe was created by three layer copper screen mesh of 100 mesh size. The heat input to the heat pipe was varied from 50 W to 250 W in five steps. The heat pipe is tested with three hybrid nanofluids made with combination of Al₂O₃ and CuO nanoparticle in DI water (Al₂O₃ 75%–CuO 25%, Al₂O₃ 50%–CuO 50% and Al₂O₃ 25%–CuO 75%). The tested hybrid nanofluid were made with 0.1% volume concentration of Al₂O₃ and CuO nanoparticle combination in deionised water. The result of the investigation showed that for the maximum heat load of 250 W considered in this work, the thermal resistance of the nanofluid with combination, Al₂O₃ 25%–CuO 75%, showed 44.25% reduction compared to deionised water.

Sadegh Motahar et al., This paper helps us to understand the solidification process of n-octadecane as a phase change material (PCM) with dispersed titanium dioxide (TiO₂) nanoparticle was experimentally studied. Experiment were performed in a rectangular enclosure cooled from one vertical side corresponding to the solid Stefan numbers in the range 0.17– 0.239. The Rayleigh number at the initial of experiment were in the range 0.92–18.3x10⁶. The rheological behavior of liquid PCM/TiO₂ sample at higher concentrations tended to Bingham fluid, thus the solidification experiment were conducted for Bingham number in the range 0–2.17. The solidification process was characterized by visualizing the progression of the solid-liquid interface as well as recording the temperature distribution inside the enclosure. Experimental results showed that heat conduction is the dominant mode of heat transfer during the solidification. Dispersing TiO₂ nanoparticle led to enhance in thermal conductance and consequently the increase in solidified volume.

An increase of 7%, 9% and 18% in solidified volume fraction was observed at the end of solidification for the mass fractions of 1%, 2% and 4%, respectively.

Mohammed I.Hasan et al., porosity after several use of nanofluids as a working medium. Water based nanofluid with 1, 2 and 3 vol% alumina nanoparticle are prepared and characterized. These nanofluid are charged to a complete vacuumed copper heat pipe made out of copper tube and lined by a porous wick. The heat pipe is equipped with a vacuum pressure and temperature sensors for evaluating its performance under different operating conditions. At the beginning, the heat pipe(HP) performance showed a significant result for using the nanofluids over the pure water. This result is later depreciated after several used and raised the concern of the stability of the nanoparticle suspension , stability in the base fluid due to the phase change of the water. Scan electron microscope (SEM) images are taken for the heat pipe wick after repeating usage; the images revealed a deposited layer of computed nanoparticles on the wick mesh surface. These particles computations developed a serious capillary and thermal resistance which in turn impact the heat pipe performance. A particle propellant wick design must be considered when nanofluids is implemented in heat pipe.

P.Gunnasegran et al., This paper helps us to understand the impact of nanoparticle concentrations on heat transfer characteristics in a LHP(Loop Heat Pipe).In this study, Al_2O_3 in water with particle mass concentration ranged from 0% to 3% is considered as the control fluid within the Loop Heat Pipe.The tests are carried out by manufacturing the Loop Heat Pipe, in which the setup consists of:Water tank with pump, a flat evaporator,condenser installed with two pieces of fans,two transportation lines(vapour and liquid lines),copper pipe sections for attachment of the thermocouples and power supply.The experimental results are verified by Finite element (FE) simulation using a 3D model based on the heat transfer by conduction process where the Loop Heat Pipe(LHP) as a whole is modelled by assuming it as a conducting medium without taking into the count of events occurring inside the Loop Hole Pipe(LHP).

Dong-Ryun Shin et al., This paper helps us to understand the study in which TiO_2 -nanofluid is used with different volume ratios as the working fluids of a thermosyphon and grooved heat pipe and examined various parameters such as volume concentration of nanoparticles, orientation, heat flux, and cooling media. Further, the study used nanofluids and dispersed TiO_2 -nanoparticles into pure water

with each cross-blended concentrations of 0.05%, 0.1%, 0.5%, and 1%. The observations are best heat transfer performance in the 0.05% concentration with thermosyphon. The study presents the enhancement of heat transfer performances with TiO₂-nanofluids, and fabricate a heat pipe from a straight stainless steel tube with an outer diameter and length of 10 and 500 mm. At the perfect condition for the pure refrigerant, the thermosyphon with 0.05% TiO₂-nanoparticle concentration gave 1.40 times higher efficiency than that of pure water.

Jian Qu et al., This paper helps us to understand the experimental investigation that was performed on the thermal performance of an oscillating heat pipe (OHP) that was charged with base water and spherical Al₂O₃ particle of 56 nm in diameter. The effects of filling ratios, mass fraction of alumina particle, and power input on the total thermal resistance of the OHP (Oscillating Heat Pipe) were investigated. Experimental results showed that the alumina nanofluids consistently improved the thermal performance of the Oscillating Heat Pipe, with an optimal mass fraction of 0.9 wt.% for maximum heat transfer enhancement. Compared with pure water, the maximum thermal resistance was decreased by 0.14 °C/W (or 32.5%) when the power input were 58.8 W at 70% filling ratio and 0.9% mass fraction. By examining the inner wall sample, it was found that the nanoparticle settlement mainly took place at the evaporator. The change in surface condition at the evaporator due to nanoparticle settlement was found to be the major reason for the enhanced thermal performance of the alumina nanofluids-charged Oscillating Heat Pipe.

Yurong He et al., This paper helps us to understand the stable aqueous TiO₂ nanofluid with different particle (agglomerate) sizes and concentrations are calculated and measured for their static thermal conductivity and rheological behaviour. The nanofluid are then measured for their heat transfer and flow behaviour by flowing upward through a vertical pipe in both the laminar and turbulent flow regimes. Addition of nanoparticle into the base fluid enhances the thermal conduction and the enhancement increase with increasing particle concentration and decreasing particle (agglomerate) size. Rheological measurements show that the shear viscosity of nanofluid decreases first with increasing shear rate (the shear thinning behaviour), and then approaches a constant at a shear rate greater than 100 S⁻¹. The constant viscosity increase with increasing particle (agglomerate) size and particle concentration. Given the flow Reynolds number and particle size, the convection heat transfer coefficient increases with nanoparticle concentrations in

both the laminar and turbulent flow regimes and the effect of particle concentration seem to be more considerable in the turbulent flow regimes. Given the particle concentrations and flow Reynolds number, the convective heat transfer coefficient does not seem to be sensitive to the average particle size under the conditions of this work. The results also show that the pressure drop of the nanofluids flow is very close to that of the basefluids flows for a given Reynolds number

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1. MATERIALS

3.1.1. SS 304 PIPES:

Stainless steels get their names from the American Iron & Steel Institute (AISI) and the Society of Automotive Engineers (SAE), who have separately created their own naming systems for steel alloys based on alloying elements, uses, and other factors. Here are some of the properties and chemical breakdown of SS304.

Chemical breakdown:

- $\leq 0.08\%$ carbon
- 18-20% chromium
- 66.345-74% iron
- $\leq 2\%$ manganese
- 8-10.5% nickel
- $\leq 0.045\%$ phosphorus
- $\leq 0.03\%$ sulfur
- $\leq 1\%$ silicon

Mechanical Properties:

Mechanical Properties	Metric	English
Ultimate Tensile Strength	505 MPa	73200 psi
Tensile Yield Strength	215 MPa	31200 psi
Hardness (Rockwell B)	70	70
Modulus of Elasticity	193-200 GPa	28000-29000 ksi
Charpy Impact	325 J	240 ft-lb

Table 3: Mechanical properties of SS304



Fig 3.1.SS304 pipe

3.1.2. TiO_2 Nanoparticles:

Titanium oxide (TiO_2) is available in the form of nanocrystals or nanodots having a high surface area. They exhibit magnetic properties. Titanium belongs to Block D, Period 4 while oxygen belongs to Block P, Period 2 of the periodic table. Titanium oxide is also known as flamenco, rutile, titanium dioxide and dioxotitanium.

Titanium oxide nanoparticles are known for their ability to inhibit bacterial growth and prevent further formation of cell structures.

Chemical properties:

The following tables list the chemical properties of titanium oxide.

Chemical Data	
Chemical symbol	TiO_2
CAS No	1317-80-2
Group	Titanium 4
	Oxygen 16

Electronic configuration	Titanium [Ar] 3d ² 4s ² Oxygen [He] 2s ² 2p ⁴
Chemical Composition	
Element	Content (%)
Titanium	59.93
Oxygen	40.55

Table 4. Chemical properties of titanium oxide

Thermal Properties

The thermal properties of titanium oxide nanoparticles are as below.

Properties	Metric	Imperial
Melting Point	1,843° C	3,349° F
Boiling Point	2,972° C	5,382° F

Table 5. Thermal properties of titanium oxide



Fig 3.2 TiO₂ Nanoparticles

3.2. METHODOLOGY:

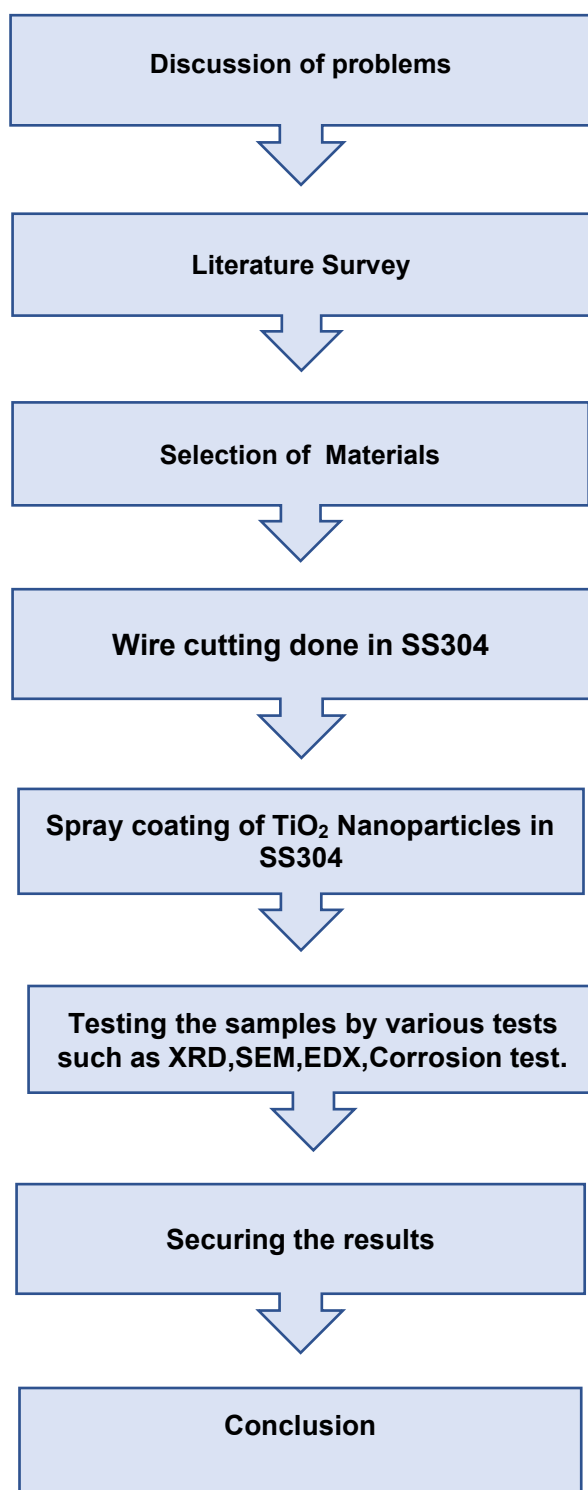


Fig 3.3 Methodology flow chart

CHAPTER 4

PROCESS AND WORK DONE

4.1 EXPERIMENTAL PROCESS:

1. The SS304 grade pipes are selected as they have good thermal properties.
2. Then the pipe undergoes EDM wire cutting process.
3. In this process, totally 8 pieces of dimensions 1cmx1cm are removed by wire cutting process.
4. Four samples are separated and then coated with TiO_2 nanoparticles by spray coating method.
5. Then both the coated and non coated samples are taken into laboratory for further tests.
6. Six samples undergoes salt spray corrosion test and two sample undergoes XRD,SEM,EDAX Tests.
7. The final results are collected.

4.2. WORK DONE TILL NOW:

1. Identified the materials required(SS304 & TiO_2)
2. Purchased the materials required
3. SS304 Pipe Went under the EDM wire cut process.



Fig4.1 . sample pieces obtained from EDM wire cut process

4.The obtained samples are now coated with TiO_2 Nanoparticles by Spray

Coating process.

5.The coated samples undergo SEM,EDAX,XRD,Salt Spray corrosion test.

6.The results are analysed.

4.3 RESULT ANALYSIS:

The results of the tests(SEM,XRD,EDX,Salt spray corrosion test) are analysed in this section.

4.3.1. TOPOGRAPHICAL ANALYSIS OF THE SAMPLE

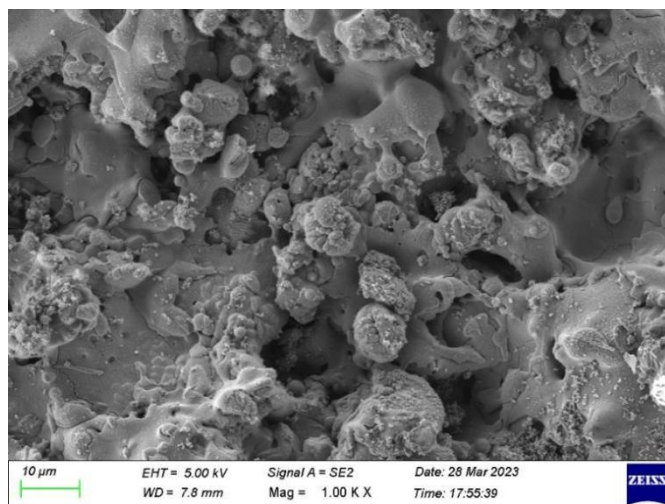


Fig.4.2. SEM Image of both coated sample

The SEM images of the coated and polished sample are studied and the changes in topography of the samples is summarized. In the coated sample, we can see that there are many pore like structures on the surface of the coating layer. These pores indicate that the coated surface underwent oxidization. The coated surface reacted with the atmosphere that resulted in oxidization on the surface of the sample. We can also see the colloidal structures in this image.

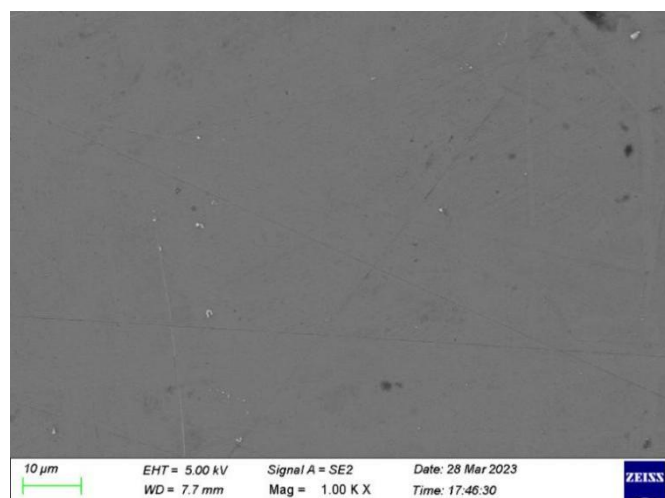


Fig 4.3.SEM image of polished sample

On the polished sample, we can clearly see the dark spots are just like shadows of the particulates as particle like structures are also visible at the centre of the dark spots. These dark spots are due to improper cleaning or handling, the most probable reason for these black spots. Even if the substrate was cleaned properly before deposition, the particles may settle at the surface during sample mounting for SEM analysis. Tissue paper lint, tape adhesive, tong or tweezers edges with some dust or tape adhesive (if you try to hold the tape with the same) etc. some sort of arcing (sparking) in the plasma during deposition is also another reason to the reason of dark spots in the polished SEM image. High deposition rates may also result in formation of such particulates sometimes.

4.3.2 ELEMENTAL ANALYSIS OF THE SAMPLE

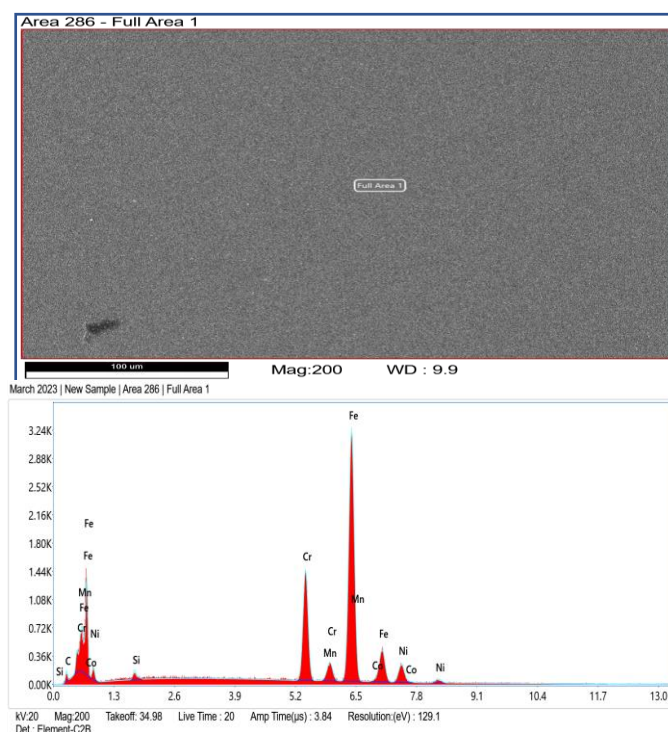


Fig 4.4.EDS Image of the polished sample

Energy-dispersive X-ray Spectroscopy (EDS) is an analytical technique that enables the chemical characterization/elemental analysis of materials. A sample excited by an energy source (such as the electron beam of an electron microscope) dissipates some of the absorbed energy by ejecting a core-shell electron. A higher energy

outer-shell electron then proceeds to fill its place, releasing the difference in energy as an X-ray that has a characteristic spectrum based on its atom of origin. This allows for the compositional analysis of a given sample volume that has been excited by the energy source. The position of the peaks in the spectrum identifies the element, whereas the intensity of the signal corresponding to the concentration of the element. The polished sample EDS is now analysed. The chemical composition of the SS304 polished sample in weight is Carbon(4.08%), Si(0.77%), Cr(17.82%), Mn(1.37%), Fe(67.92%), Co(0.88%), Ni(7.16 %). Here in this case, Iron is a major constituent of the composition of sample with 67.92% thus this material has capability of undergoing rusting but not undergo corrosion. The second highest constituent is Chromium with 17.82%. Chromium has excellent corrosive resisting properties that protects the metal from getting corroded. Third major constituent is Nickel with 7.16%. Nickel enhances the important properties such as formability, weldability, ductility, while increasing corrosion resistance in some applications. This graph also depicts that Fe peaks higher at 3.24K at 6.5.

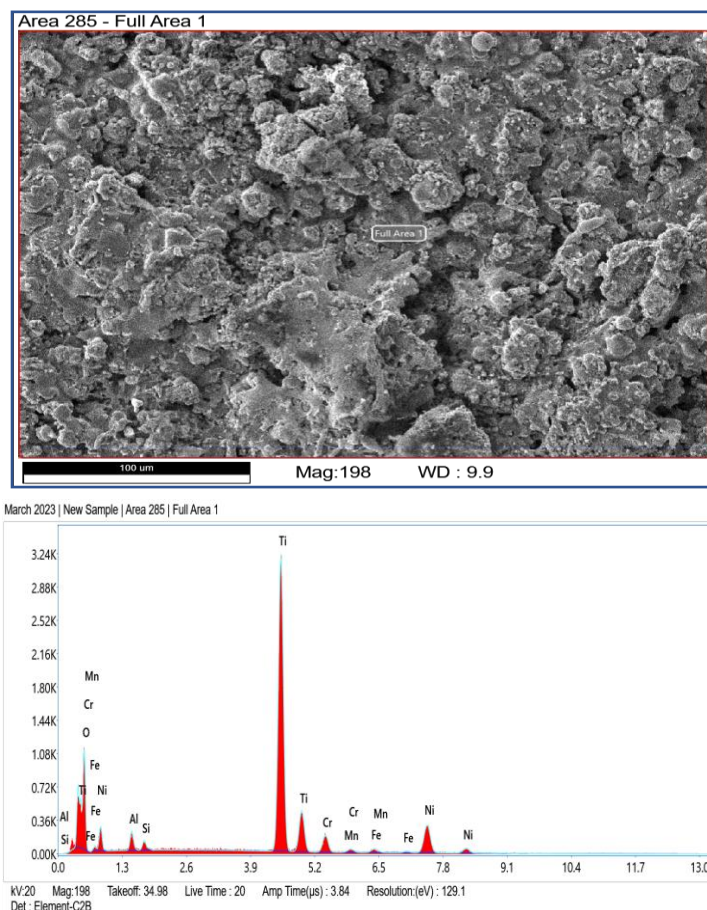


Fig.4.5. EDS image of the coated sample

The Coated sample EDS is now analysed here. The Coated sample chemical composition is of O(34.30%), Al(1.69%), Si(0.70%), Ti(45.93%), Cr(4.03%), Mn(0.45%), Fe(1.05%), Ni(11.83%). Since sample is coated with TiO₂ nanoparticles, Titanium is the major constituent in this sample with 45.93%, Thus the material's boiling and melting point changes due to the influence of titanium as they have higher melting and boiling point than SS304 material. Oxides occupy the second major constituent in this sample with 34.30%. Normally SS304 do not form oxides even though they are exposed in the atmosphere. But here in this case, due to the influence of titanium the chemical properties of the sample is changed and thus it also results in oxide formation. Nickel occupies the third major constituent in this sample with 11.83%. It results in improving the important fabrication properties like weldability, ductability, formability etc. Nickel provides corrosion resistance for some applications but in this sample due to the influence of Titanium they undergo oxidization hence it does not resist or affect corrosion process. This graph also depicts that Ti peaks higher at 3.24K in between the range of 3.9 to 5.2.

4.3.3 CORROSION TEST

Salt spray corrosion test has been performed, due to the presence of nanoparticle coating over the surface of the sample. This particular method of Salt spray method is used in this project as the pipes are mostly used in oil and gas industries, boiler industries will be present in a more saltier environment. So this test will be a simulation test for us to study whether the coating prevent corrosion or get corroded. TiO₂ Nanoparticles are coated on the surface of the sample as they have excellent melting and boiling point. But the results states that TiO₂ is a good corrosion resistance element because even though it has lesser density (4.26) compared to uncoated sample (8.01). Also the corrosion rate per year is higher in uncoated sample (0.017204918) than the coated sample (0.011135873). Also the corrosion mils per year is higher in uncoated sample (8.120721434) than the coated sample (5.256132198). But the polished sample has lost more weight (in grams) than the coated sample. (Polished-0.024, Coated-0.02).

4.3.4 X-RAY DIFFRACTION TEST ANALYSIS

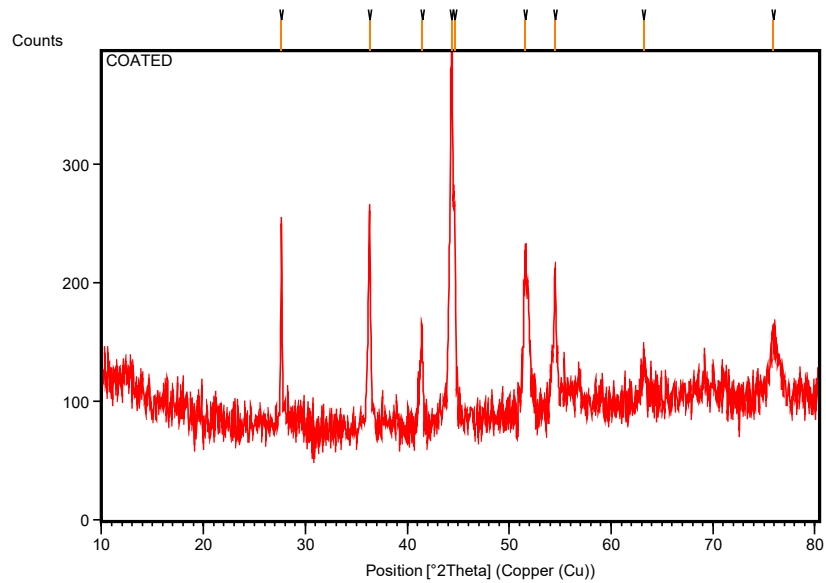


Fig 4.6.XRD graph of both coated sample

The results from the X-Ray diffraction test clearly shows that the values from the XRD graph clearly coincide with the JCPDS value. This clearly shows that the material coated on the surface is Titanium Dioxide as the values coincide with the JCPDS values. The JCPDS Values of the coated samples are (3.22800, 2.47576, 2.17949, 2.04333, 2.02882, 1.77256, 1.68435, 1.47199, 1.25297) and they coincide with the default JCPDS values.

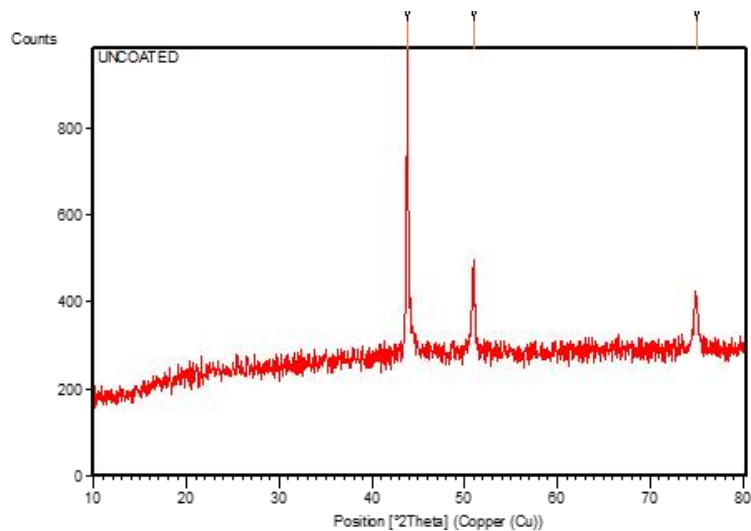


Fig 4.7.XRD graph of uncoated samples

The results from the X-Ray diffraction test clearly shows that the values from the XRD graph clearly coincide with the JCPDS value. This clearly shows that the material coated on the surface is Titanium Dioxide as the values coincide with the JCPDS values. The JCPDS Values of uncoated samples are (2.06603, 1.79160, 1.26653) and they also coincide with the default JCPDS values. Thus XRD test results states that Titanium is coated on the surface.

CHAPTER 5

CONCLUSION

In this project phase, we have worked in producing a review article based on the title “A COMPREHENSIVE REVIEW ON EFFECT OF NANOPARTICLES OVER THE THERMAL CHARACTERISTICS OF HEAT PIPES” and a research article based on the title “EXPERIMENTAL INVESTIGATION ON THE THERMAL CHARACTERISTICS OF VAPOUR CHAMBERS USING NANOCOATING OF TITANIUM OXIDE” as part of our project. From the experiment point of view we have identified and purchased the materials required and we have done the wire cutting process. After the Wire cut process, the samples are prepared by polishing the surface which makes it ready for testing. Then the samples undergo thermal spray coating process in which Titanium Oxide nanoparticles are coated on the surface of the samples. The samples now undergo tests like salt spray corrosion test, Scanning electron Microscope (SEM), X-Ray Diffraction tests (XRD), Electron diffraction Spectroscopy (EDS). The results are analysed and it states that Titanium can be used as a corrosive resistant material and the structural, chemical composition has been studied. The idea of this project is to find the cheapest corrosion prevention solution. Corrosion in real life is seen in brake axles during rainy season, in boiler industries during three point situation due to the change in temperature and pressure, it creates a situation that supports corrosion growth in the boiler, we can also see corrosion in the oil wells that extract oil from the ocean bed and due to the saltiness of the sea and the salty nature and environment corrosion occurs there also. In order to prevent the corrosion which occurs through nature we came up with this idea of using nanoparticles. Nanoparticles are highly influential materials that influence the physical and chemical properties of the material and change the abilities of the material. Due to their influenced properties they control their whole properties and control them. We chose Titanium Oxide because they have high boiling and melting points that helps us to test in higher conditions. The results also showed that they have higher corrosion control and they also help us to study the change in physical and chemical properties.

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