The liquid ring pump

The performance of a two-stage liquid ring pump with water as the sealant liquid was investigated under stand-alone conditions. The parameters varied in this experiment were the cooling water flowrate and inlet air volumetric flowrate which affects the sealant water temperature and pumping speed respectively. Pressure and temperature readings were taken to calculate the compression work and efficiency across the liquid ring pump. It was found that efficiency improved at higher cooling water flowrates and lower sealant water flowrates. As the inlet air mass flowrate was increased, it was also observed that the suction pressure, pumping speed, and compression work increased. These trends compare well to similar investigations done in literature. Assumptions made to describe the performance of the LRP were isothermal compression, ideal gas, dry air as inlet gas, and no loss of energy to the surroundings. Energy balance done across the liquid ring pump showed an agreement to literature (1) that isothermal compression was found to be more thermodynamically efficient compared to an adiabatic process. Further work can be done by investigating he pump's performance using different sealant liquids, inlet gas moisture content, and in conjunction with reflux/reboiler and reflux/condenser.

Problem Statement

Morton Labs Inc. has commissioned an independent evaluation of their liquid ring pump rig. They would like a report on the performance of the pump under a wide set of conditions and its suitability to operate with the Reboiler/Condenser and Reflux/Condenser rigs in their plant.

Group A3 was required to plan and carry out experiments that can provide data for such evaluation. The evaluation should include mass and energy balance calculations, performance data and an analysis and description of the behaviour of the pump as well as any suitable model.

You will have access to their facility and will be shown how to operate the equipment.

Introduction

The concept of vacuum has long been the subject of interest of philosophers since the times of the Ancient Greeks due to its profound uniqueness and was recreated by physical means with the creation of what can now be described as the first vacuum pump by Otto von Guericke in 1650. (2)

Vacuum pumps have been steadily improved and advanced since then but it was not until huge advances in the late 19th and early 20th century paved the path to what would become a vital organ in several industries such as chemical, pharmaceutical and food industries. (2) In a typical paper mill for example, vacuum is mainly used to assist the removal of water in wire drainage and pressing sections in addition to several other purposes. (3) For such an industry, liquid ring vacuum pumps are utilized in order to create the vacuum needed for the mentioned processes. (4)

In order to produce vacuums in the most efficient manner, the behaviour and performance of liquid ring pumps needs to be studied in order to reduce costs of operation and reduce energy consumption. Several investigations such as those by Powle and Kar (4) and Chilvers and Love (5) on measuring the behaviour of liquid ring pumps have been conducted due to the importance of determining performance.

The objective of this set of experiments is to determine the performance of the 2 phase Hicks Hargreaves SLR type liquid ring pump the located on the B-floor of the Morton Laboratory. Performance can be described by varying flow conditions of the sealant water and cooling water supplied to the liquid ring pump and taking pressure and temperature measurements accordingly.

This report will start by describing the operation of liquid ring pumps and the technical theory used to describe their performance, followed by the experimental plan and the methodology. The data collected will then be analysed in order to create trends describing the compression work and the isothermal efficiency of the pump in question. The report will be concluded by suggesting possible areas to be further studied in addition to answering the objective of the experiment.

Background

Liquid Ring Pump (LRP)

The liquid ring pump operates as a vacuum pump using liquid as a compressing agent. It consists of a metal cylindrical body containing an impeller and blades set off centre with respect to the central line of the pump. The liquid ring pump must then be partially filled with a liquid which will act as the sealant and results in forming a vacuum. This is illustrated in figure 1A. The sealant liquid can be either water, oil or a solvent, depending on the application of the pump. When the impeller starts to rotate it throws the liquid in the pump against the walls by centrifugal force. This will cause the impeller blades closest to the wall to be completely submerged in the liquid sealant and the impeller blades furthest away from the wall create a void space with the liquid ring. This is because the impeller is set off centre.

This void space sealed off by the liquid and the impeller can be seen by looking at figure 1B. As the impeller rotates anti-clockwise from the top to the bottom, the area of void between the impeller and liquid sealant expands. This creates a suction force which draws gaseous fluid into the pump inlet, as the impeller carries on rotating anti-clockwise from the bottom to the top the liquid is forced closer to the impeller compressing the void space and creating a compression force which pushes the gaseous fluid out of the pump outlet along with a little bit of the liquid sealant, this is because the liquid is highly turbulent inside the pump. (6)

A two stage liquid ring pump is the same as described above but with two cycles in series; so that the outlet from the first stage is the inlet of the second stage. Typical values of the vacuum pressure in a two stage pump decreases to 25 mmHg from 35mmHg in a single stage pump. This shows it is much more efficient at creating the desired low vacuum which ranges from 22. 5mmHg to 750mmHg.

(B)

(A)Figure 1: Illustration of liquid ring pump operation (7)

Liquid ring pumps are commonly used on reflux / condenser and reboiler / condenser systems. One such system is the removal of air from steam surface condensers and other industrial processes. The liquid ring pump would be employed to evacuate air and any non-condensable gases from a condenser; the gas removal is done to eliminate the insulating effect of the gases present which affects the heat transfer between the steam and cooling medium. This greatly improves the efficiency of the heat transfer system and results in a smaller condenser surface area required, therefore saving space and costs of running a larger condenser. Typically for running such systems a two-stage liquid ring pump would be favoured to create a hogging operation. The first stage of the pump is used to evacuate the air from the condenser at very high pressures and then the second stage is used to optimize the efficiency of the pump and reduce the amount of peak power required. (8)

Vacuum pumps are important units in plants that are involved in many applications like processing food, plastic processes, medical process that requires, etc. There are three types of vacuum pumps which can be concluded as molecular pumps which use very high speed jet of fluid, positive displacement pumps that enlarge the cavity and seal it off in frequent and entrapment pumps that traps fluid in solids. A liquid ring pump falls under the displacement pumps category, however there difference that distinguishes it from other displacement pumps. This is due to a liquid ring being formed, it creates a high convective heat and mass transfer phenomenon which dissipates the thermal effect of compression and achieves near isothermal behaviour. The effect of instantaneous convective heat and mass transfer is so rapid that the gas outlet temperature is noted to be close to the sealant inlet temperature almost instantaneously. Because of this effect the discharge temperature remains roughly constant, and since the volumetric flowrate also remains nearly constant then with high suction pressure the mass discharge can be enhanced. This causes the liquid ring pump to have faster evacuation during start up and faster turnaround during cycling. (1)

Liquid ring pumps can use a variety of liquids, water is the most common, and the choice is generally related to the pressure you wish to be operating at. Oil is also commonly used as a liquid sealant, since oil has a very low vapour pressure; it is typically used in air-cooled systems. The liquid ring pump is also ideally suited for solvent recovery such as toluene provided the cooling water keeps the vapour pressure of the sealant down to produce the required vacuum. Ionic fluids also can be used to reduce the pressure from about 70mbar to below 1mbar. (9)

Cavitation is considered a major issue that is associated with liquid ring pumps due to the fluid environment creating low pressures. At very low pressure, 35 mmHg, water boils at 31. 7 CËš. Therefore, it is essential to keep the sealant at low temperatures by supplying a cooling water flowrate to the system. Inertial cavitation is caused when the pressure falls below the vapour pressure and cause bubbles to form. These bubbles then start to collapse due to the high pressure of the surrounding medium as the pump starts to compress. As the bubble is collapsing the pressure and temperature inside rapidly start to increase, the bubble will eventually collapse, and this releases the gas into the surrounding liquid with a violent mechanism where the energy is released in a shock-wave. This can cause a series of craters and holes along the impeller this can reduce efficiency of the pump and can be seen in figure [2].

Figure [2]: Cavitation

We can see the region of cavitation caused by the outlet water temperature, absolute suction pressure and air flowrate illustrated in figure [3] below.

Figure [3]

Figure [3] shows how a pump can operate within a safe region and then be carried into the cavitation region with only an increase in temperature. The graph also shows how the liquid in the pump vaporizes under certain conditions. For our experiment it makes sense to control the safe operation of the pump by supplying a cooling water stream. This will keep the temperature down and out of the cavitation region. It is also easier to control as the air flowrate depends on the rig that the liquid ring pump may be connected up to. And the suction pressure will have local variation within the pump. (10)

Orifice meter for determining air flowrates

The flowmeter used by the DeltaV software in the control room, was used to provide data on inlet air flowrates into the liquid ring pump and was unfortunately faulty. This meant the real time recordings of air flowrates could not be supplied. Thus, calibration of the orifice meter was necessary to determine the inlet air flowrates.

Figure ?: Orifice meterA square-edged orifice with radius taps was used to calibrate the inlet air flowrate into the Liquid ring pump. Pressure tappings attached to mercury manometers were located one pipe diameter upstream and one-half pipe diameter downstream from the orifice plate as shown in Figure ?.

Bernoulli’s equation for incompressible, inviscid flow along a streamline (11) without shaft work:

Where is the inlet pressure (upstream pressure in this case), Pa is the outlet pressure (downstream pressure in this case), Pa

are the inlet and outlet velocity respectively, m s-1

is the density of the fluid, kg m-3

is the gravity acceleration, m s-2

, are the inlet and outlet elevation respectively, m

The continuity equation gives (11)

Where and are the inlet and outlet cross-sectional area respectively, m2

The volumetric air flowrate across the orifice plate can be expressed by substituting Eq. (2. 2. 2) into Eq. (2. 2. 1) to give

Where is the volumetric air flowrate across the orifice plate, m3 s-1

is the coefficient of discharge

is the orifice cross-sectional area, m2

is the pipe cross-sectional area, m2

A typical equation relating the discharge coefficient, as a function of Î² and Reynolds number, Re, was adapted to calibrate the orifice meter

With the conditions of and

Where is the viscosity of the fluid, Pa. s

To calibrate the air flowrate across the orifice plate, the cooling water flowrate was kept constant and the pressure drop across the manometers were taken for 10-70 number of turns on Valve 11. 6 for varying cooling water flowrates. From typical values of 0. 61-0. 65 (12), was used as the initial guess for iterations to take place. After three iterations, the values of between the corresponding iterations differ within an order of 10-6 and at the third iteration were used for calculations in this report. Where did the valve come from? Relate to diagram?

2, 5, 8, 11 what?

Figure 2: Calibration of inlet air mass flowrates across orifice plate give similar trend and magnitude for varying cooling water flowrates

Figure 2 indicates that the varying cooling water flowrates do not affect the air mass flowrates across the orifice plate. Thus, the inlet air mass flowrates depends only on the number of turns on Valve 11. 6. Average inlet air mass flowrates for cooling water at 2, 5, 8, and 11 kg h-1 were used to produce the following equation in Figure 3 which will be the calibration used in this experiment.

Figure 3: Calibration of averaged inlet mass air flowrate across orifice plate

Assumptions

Temperature Factor

Figure 4: Double Stage Pump (13)

The suction pressure created falls within the range of approximately 106 to 531 torr while the temperature of sealant water used entered the pump at approximately 55°F. These conditions fall within a region where the gradient of the graph is very gentle and the value of the temperature factor is around 1. 0. Therefore, the temperature factor to be applied to the flowrate of sealant water is approximately the same even as inlet pressure changes. Also, even as the cooling water flowrate was changed, the sealant water temperature was observed to remain around 55°F. The temperature factor to be applied would not be greatly affected by either of the two operating variables, namely the cooling water flowrate and the inlet air mass flowrate which affects the suction pressure. Since the temperature factor is approximately 1. 0, it can be assumed that the mass flowrate of sealant water entering the pump and leaving the pump to be the same, making the vaporisation of air negligible. This assumption is investigated by performing a mass balance across the pump taking into account vaporisation of air during the compression process.

Inlet air

It is assumed that the inlet air into the Liquid ring pump contains no moisture, thus we refer to the inlet air as dry air.

The heat exchanger is assumed to have 100% efficiency in heat transfer between the pump, sealant water, and cooling water streams. Assuming no heat loss to the surroundings, the compression work done by the pump is equal to the heat gained by the cooling water in the heat exchanger. For the purpose of calculating efficiency of the Liquid ring pump for this experiment, it is found to be more ??? to calculate compression work from the cooling water heat gain.

Steady State

Vapour pressure

Vapour pressure refers to the pressure in the gas phase when the liquid and gas phase of a system are in equilibrium. The vapour pressure of the sealant liquid into the Liquid ring pump plays an important role in determining the pump capacity. At higher temperatures of sealant liquid, the vapour pressure increases and more vaporisation occurs, causing a lower flowrate of air into the pump which results in low pump capacity.

Although it might seem that maximum cooling of the sealant water might be a good idea, care must be taken that the sealant water temperature do not fall so low that cavitation might occur in the Liquid ring pump. [more on cavitation in limitations section] In this experiment, the temperature of the sealant liquid is varied by changing the cooling water flowrates. The relationship between vapour pressure and pump capacity is investigated.

From Antoine’s equation, the vapour pressure of a liquid within a range of temperature can be determined (14)

Where T is the temperature, K

is the saturation vapour pressure, mmHg

are constants for specific materials. For an air-water system, the standard Antoine coefficients are A= 8. 05573, B= 1723. 64, C= 233. 076 °C, valid between temperatures of 0. 01 °C and 373. 98 °C. (15)

A relationship between the vapour pressure and temperature can be obtained from the Clausius-Clapeyron equation (16)

Where T1 and T2 are temperatures at condition state 1 and state 2 respectively, K

and are vapour pressures at T1 and T2 respectively, Pa

is the heat of vaporisation, kJ/kg

Isothermal System

work done across T2 to T4 equals T7 to T6 T4, 6, 7?

The compression process of a liquid ring pump can be approximated to an isothermal operation at inlet sealant water temperatures. (1) During compression, mechanical energy is converted to compression work and dissipated as thermal energy. The liquid ring formed in the pump provides high heat convection and mass transfer which dissipates the thermal energy, creating a near-isothermal operation. This phenomenon occurs in such a short time scale that the system reaches equilibrium rapidly, and the outlet gas temperature approximates the inlet sealant liquid temperature. Mallick (1) describes this as an “ achievement of highest degree of thermodynamic efficiency of compression.” [Need temperatures to prove this]

Compression work

From the First Law of Thermodynamics, isothermal compression work of an ideal gas can be expressed by (16)

Where W is work, J

P is absolute pressure, Pa

V is total volume of the system, m3

Assuming ideal gas behaviour applies (verify this!),

Where m is mass, kg

V1 is the inlet volume, m3

V2 is the outlet volume, m3

R is the gas constant, Pa m3 kg-1 K-1

T is the temperature, K

For an isothermal system (17)

PV = constant

Where Wc is the compression work, J

Equation ? is divided by time t, to express the compression work,

Substituting

= m/t = Ï 🚺

Where is the mass flowrate, kg s-1

t is time, s

And equation ? in equation ?, the compression work of a vacuum pump at any pressure P, for an isothermal system can be derived to be (4):

Where is the pumping speed of the liquid ring pump

is the theoretical power consumed for an isothermal process, kW

Pump efficiency

The efficiency of the liquid ring pump is a vital factor in deciding the suitability of the pump for its purpose. Through experimental investigation, we varied cooling water flow rate and air mass flow rate to determine the condition where the liquid ring pump is the most efficient. From theory, we have assumed an isothermal operating condition which leads us to calculating the efficiency, of the pump as:

Where

Wiso, c is defined as the compression work done under isothermal conditions

Wactual, c is defined as the enthalpy gain and Wactual, c = m Cp Î” T. Units?

m is the sealant water mass flowrate, units?

Cp is the specific heat capacity of the sealant water (4. 912 KJ/Kg. K)

Î” T is the measured difference in discharge and suction temperatures in

which our case will be (T6 -T7) (18) Where have they come from?

Figure 5: Title (19)

3. 0 Mass and energy balance

3. 1 Mass balance

During compression in the liquid ring pump, mechanical work is converted to thermal energy and dissipated, potentially vaporising the sealant water used for compression. Assuming the inlet air is dry air with no water content, the mass balance across the LRP is:

Mass balance on the gas component

Assuming

This can be rearranged to give

Where is the humidity ratio obtained from the psychometric chart for the air-water system at standard atmospheric pressure (20). By determining the relative humidity, RH, the value of HR at any temperature can be determined from the psychometric chart.

Where is the vapour pressure which can be determined by Eq. ? (Antoine), Pa

is the saturation vapour pressure, Pa

Mass balance on the liquid component

3. 2 Energy balance

Total energy balance of a unit mass of fluid is given by (14)

Where are internal energy at the inlet and outlet respectively, J

is the gravitational acceleration, m s-2

z1 and z2 are the elevation at inlet and outlet respectively, m

and are the velocities at inlet and outlet respectively, m s-1

q Heat absorbed from the surroundings units?

Ws work done by the fluid on the surroundings units?

Assumptions made for the energy balance across the pump:

since the system is operating horizontally with no elevation between inlet and outlet

Kinetic energy is assumed to be negligible since it is insignificant compared to enthalpy change.

Negligible heat loss from the system, . This assumes an adiabatic process.

Substituting the relation

And

Where h is the specific enthalpy, kJ kg-1

The energy balance equation reduces to

Which is

Where and are the inlet and outlet mass flowrates respectively, kg s-1

and are inlet and outlet specific enthalpy respectively, kJ kg-1

Methodology

Apparatus

Figure 6: Process Flow Diagram of Experimental Set-up

Liquid Ring Pump

Sealant Water Tank

Scrubber

Thermocouples

Mercury Manometers

Rotameter

Orifice Plate

DeltaV system

Experimental design

Firstly, we identified two operating variables that could be varied to investigate the performance of the pump. The two variables are the inlet air flowrate and the storage tank cooling water flowrate.

The inlet air flowrate could be manipulated by a flow control valve over a range of 8 to 70 turns. By calculating the pressure drop across an orifice plate and plotting a calibration curve, we were able to get the mass flowrate associated with the number of turns on the valve.

The storage tank cooling water could be manipulated over a range of 0. 5 to 12. 5 m3h-1. The adjacent flowmeter gives a measurement of the cooling water flowrate into the heat exchanger around the sealant water storage tank.

A full set of measurements were taken to obtain pressure, flowrate and temperature data as we changed the operating variables. Pressure data was obtained for the pressure drop across the orifice plate, and the suction, interstage and outlet pressures for the pump through mercury manometers. Flowrate data was taken from a rotameter that measured the volumetric flowrate of the sealant water. Temperature data was extracted by the DeltaV logging software in the control room.

Experimental Procedure

The following procedure was conducted over two experimental runs. Through repeating the procedure, we were able to test the reproducibility of our results and reduce the effect of random errors on our results.

Set and maintain cooling water flowrate at 2m3hr-1.

Starting with the maximum air flowrate at 70 turns we waited for steady state to be achieved before taking the manometer readings for suction, interstage, outlet, orifice plate and rotameter readings for the sealant water flowrate.

The air flowrate was then decreased to 60 turns followed by 50, 40, 30, 20 and 10 turns, all the while ensuring that steady state is reached before taking the readings.

The full range of measurements from 70 to 10 turns for the inlet air flowrate was similarly taken at cooling water flowrates of 5, 8 and 11m3hr-1.

Limitations

In determining if the system is at steady state, the flowrate readings that can be monitored from the control room will provide good indication once the rate stabilises. However, the range of the flowmeter is limited beyond 119m3/hr (between 40 and 50 turns on V11. 6). Therefore, the mercury manometer that reads the pressure drop across the orifice plate should be used to determine steady state after 40 turns on V11. 6. A calibration curve will be plotted to relate the inlet air flowrate and the pressure drop across the orifice plate for mass flow calculations.

Also, the flowmeter was faulty on our second run which meant that we would have to solely depend on our calibration curve to determine the inlet air mass flowrate at any number of turns.

Analysis of results

In the investigation of the performance of the two stage liquid ring pump, we ran the pump under different operating conditions by varying two variables; the air mass flowrates into the pump and cooling water flowrates. Pressures of the suction, interstage and outlet of the pump were measured and used to evaluate the pump's performance at different conditions, hence determining the efficiency of the pump. As the behaviour of inlet air mass flowrate, sealant water flowrate, suction pressure, compression work and pumping speed showed almost identical trends for different cooling water flowrates, an average of the four measurements were used.

Sealant Liquid

The sealant liquid used in the experiment is water and the compressed fluid is air. Before starting the run, the pump is filled with a specific level of water to ensure that there is sufficient sealant liquid to create vacuum. As the sealant fluid shares the same space in the pump as the fluid to be compressed, it would be expected that as the flowrate of the latter is increased, the flowrate of the sealant liquid decreases.

Figure 7: Average Sealant Water Flowrate vs Inlet Air Mass Flowrate

From figure 7, it can be seen that as the inlet air mass flowrate increases, the sealant water flowrate into the pump decreases. This is in line with the expected trend since the compressed air occupies a much greater volume in the pump at higher air mass flowrates.

Suction Pressure

Vacuum is created by the liquid ring pump due to the pressure difference between the source and the pump inlet. In the experiment, the source is air at atmospheric pressure and the inlet pressure is the suction pressure created by the pump. A low suction pressure would translate to a big pressure difference, creating vacuum. (21)

Figure 8: The average inlet air mass flowrate for varying cooling water flowrates was plotted against suction pressure

Figure 8: shows the trend we obtained where suction pressure increases as inlet air flowrate is increased. This shows that at lower air flowrates, more vacuum is created at a low suction pressure. As the air flowrate is increased, the ability to create vacuum decreases resulting in a higher vacuum pressure.

Figure 9: The relationship between dry air capacity and suction pressure at a temperature of 20 °C obtained from literature. (22)

As it is assumed that dry air is used and that its density remains constant throughout, the experimental results in Figure 8 can be compared to results obtained from literature in Figure 9. A similar trend is observed where there is the suction pressure is greater as the dry air capacity increases.

Figure 10: Table categorising the degree of vacuum according to the absolute pressure of operation. (23)

This experiment operates within a range of suction pressures which averages to approximately (1. 41-6. 00) x104 Pa abs. From figure 10, the range categorises the liquid ring pump as one that creates low vacuum. Low vacuum is sufficient in many industrial applications such as distillation in the petrochemical industry which keeps the liquid ring pump as a relevant piece of plant equipment.

Compression Work

(Sample calculations for a cooling water flowrate of 11 m3h-1 at 30 numbers of

turns) shifted to appendix

To calculate compression work under isothermal conditions, we can use Equation 3. 7. 11

Figure 12: shows that greater compression work is done by the pump with increasing suction pressure.

From figure 12(above), it can be seen that greater compression work is done with increasing suction pressure. Based on the inlet air mass flowrate that we used, the suction pressure we created with the pump ranges from ~106 to 531 torr. The graph of the suction pressure against compression work shows a similar trend to literature values shown below in figure 11(below) for the same range.

Figure 11: Effect of suction pressure compression work (4)

Removed figure 13

Effect of Inlet Pressure on Pumping Speed

Figure 15: Pumping Speed at different temperatures of sealant liquid (4)

It can be seen from the graph Figure 15 that the change in pumping speed gradually becomes smaller.

The inlet pressure (suction pressure) that we obtained from varying the inlet air mass flowrate falls within the range of around 106 to 531 torr. Therefore, we should obtain the same trend of pumping speed with increasing inlet pressure.

Figure 16: Pumping speed changes with increasing suction pressure

Replaced the graph with a newer one showing the right denotation for units on the y axis

Figure 16 shows that the experimental results obtained agree with results obtained from literature. With increasing inlet pressure, the pumping speed increases while the gradient of the graph decreases.

5. 5 Efficiency

Figure 17: Plot of Isothermal Efficiency Vs Sealant Water Mass Flowrate

Figure 17 shows that isothermal efficiency decreases with increasing sealent water flowrate. This result agrees with theory as we know from theory, the efficiency of the pump is affected by the vacuum capacity, and with an increase in sealent water flowrate, more vapour will be formed from the increased amount of sealent water forming the ring-liquid when the vacuum pressure approaches the vapour pressure of the sealent liquid. The increase in vapour volume released from the increase in sealent water will decrease the vacuum capacity and therefore reducing efficiency.

Figure18: Plot of Efficiency Vs Cooling Water Flowrate

Figure 18 shows that a higher cooling water flowrate will result in higher efficiency. The above trend is derived from the isothermal efficiency of the system at a fixed sealant water flowrate of 0. 27 kg s-1. The cooling water flowrate is related to the enthalpy gain of the sealant water and consequently the isothermal efficiency. A higher flowrate would mean that the enthalpy gain is lower and that isothermal efficiency is higher which can be seen from equation 2. 8. 1.

From the above results we can therefore conclude that the liquid ring pump is most efficient at the highest cooling water flowrate and a sealant water flowrate of 0. 27 kg s-1 which translates to air flowrate at 60 turns flowing into the pump.

Remove