Guidelines for evaluation of liquid ring vacuum pump performance

Scope

This Technical Information Paper is provided to assist in evaluating performance of single stage, liquid ring vacuum pumps. Cone ported liquid ring vacuum pumps are a common source of paper machine vacuum in the pulp and paper industry. This paper is also applicable to other designs of single stage liquid ring vacuum pumps such as flat plate ported. Liquid ring vacuum pumps are typically equipped with two top suction flanges and two side or bottom discharge flanges. Often the suction flanges are manifolded together as are the discharge flanges.

Safety precautions

Caution should be taken when utilizing any of the processes or procedures outlined in this paper. Proper lockout and isolation of energized equipment is critical when performing internal inspections. Appropriate PPE should be worn according to mill policy as well as following mill policy when on ladders or working in an elevated position. When taking air flow measurements on operating equipment, caution should be exercised when working in close proximity to open ports where high vacuum may draw hands fingers or other objects into them.

Summary

Liquid ring vacuum pumps are key components of the paper machine. Vacuum pump performance has a direct effect on energy consumption, performance in the forming and press sections, fabric life and dryer section steam requirements. Commonly used vacuum pump field evaluation procedures are visual inspection of pump internals via Boroscope and air flow measurements. This paper will discuss the merits and limitations of these as well as provide details for using the orifice plate testing procedure to properly field-test vacuum pumps.

Definitions

- **Vacuum**: A pressure less than atmospheric pressure.
- **Orifice**: A reamed hole in the orifice plate calibrated to pass a determined volumetric flow rate of air at specific vacuum levels.
- **Seal water**: The water supplied to a liquid ring vacuum pump which forms a liquid seal between the inlet and discharge ports, removes the heat of compression and lubricates the packing rings sealing the shaft.
- **Inlet manifold**: The pipe which joins the two inlet flanges of a vacuum pump.
• **Discharge manifold:** The pipe which joins the two discharge flanges of a vacuum pump.

• **PTFE:** Polytetrafluoroethylene (commonly referred to as Teflon™).

• **Analog vacuum gage:** An analog gage (needle on a face) shows immediate minor fluctuations in vacuum level tested. Analog gage is better than digital gage for reading fluctuations in tested vacuum.

• **Regulating valve:** A manual valve used to control the seal water flow to achieve maximum stable vacuum.

• **Shut off valve:** A “closed or open” valve, typically solenoid valve, is not acceptable for regulating the seal water flow for the orifice test.

**Vacuum pump**

This section describes how a vacuum pump moves a volume of air and can incur losses over time that can be measured by various methods. Figure 1 shows that a liquid ring vacuum pump is a positive displacement device that moves a constant volume of air at less than atmospheric pressure.

**Figure 1.** Liquid ring vacuum pump: A cylindrical housing with an off centered rotor moving a ring of water inside the housing and shaped by the housing. (1) Atmospheric air by its own energy enters the inlet port and inlet segment of the pump and fills a volume at less than atmospheric pressure. (2) The trapped air volume is compressed by the liquid ring through the compression segment. (3) The compressed air volume is forced out of the discharge segment and discharge port of the pump as it is higher than atmospheric pressure. (4) Note the very important seal preventing the high-pressure discharge air from passing into the inlet segment and robbing space from new air entering the inlet segment of the pump.

**Figure 2.** Vaneslip: When an iron liquid ring vacuum pump is run for years, iron oxide (rust) is removed, and the close tolerance between the rotor vanes and the surface of the seal segment opens to larger than original. With this enlarged clearance, some of the high-pressure discharge air can bypass to the lower pressure (vacuum) inlet segment of the pump. This robs space for new air to enter the pump. The high-pressure discharge air bypassing into the inlet segment is called “vaneslip” (Figure 2). The orifice test method measures the new air entering the inlet segment (actual current pump capacity), which may be less than the original air capacity by the volume occupied by vaneslip and can be compared to the original capacity.
Air flow measurement using a calibrated orifice plate

This is the most accurate method of determining air flow to the pump and is the focus of this Technical Information Paper.

This test procedure is to be used as a benchmarking tool to empirically check vacuum pump output. Because of the many factors described in the following paragraphs that affect the accuracy and repeatability of the test results, the calculated results may be used to compare pump performance to the original vacuum pump manufacturers’ marketing performance curves. Tests performed by most vacuum pump manufacturers are done using the Heat Exchange Institutes’ (HEI) guidelines for vacuum pump testing. The HEI test procedure requires the tests to be done under a controlled testing atmosphere and has greater accuracy and repeatability than this flat plate orifice test method. Factors such as orifice sizes, pressure tap locations, and vacuum gauge accuracy will influence the accuracy and repeatability of the test results. When comparing the test results of a single vacuum pump to a prior test of that pump, one should use the same orifice hole sizes, the same pressure tap locations, and calibrated vacuum gauges.

Orifice plate construction and quality are very important influences on the test results. Accuracy and repeatability will be greatly affected by plate thickness, material of construction, surface finish, squareness of orifice hole edges, and the presence of burrs, chamfers, dings and corrosion. Care should be used in storing plates between uses to prevent damage. Recommended orifice plate construction material and dimensions with tolerances are given in Appendix A.

Materials

The following materials are needed to perform an orifice plate test for vacuum pumps:

- Analog vacuum gauge(s) – The vacuum gauges must be calibrated, with at least 114.3 mm (4.5 in.) faces and accuracy of + 1%.
- Pipe fitting – The pipe fittings must be sized to fit the vacuum gauges to the gauge taps located on the vacuum pump inlets.
- PTFE tape or paste – The PTFE is to protect and seal the vacuum gauge and pipe fittings when installed.
- Rubber gasket(s) – The rubber gasket(s) must be the size of the pump or manifold inlet flange face(s) and are used to provide a seal between the orifice plate(s) and pump or manifold inlet(s). Layouts of gaskets per pump flange size are shown in Appendix A.
- Rubber stoppers – Rubber stoppers are used to plug holes in orifice plate to create vacuum differential.
- Orifice plate(s) – Layouts of orifice plates per pump flange size are shown in Appendix B.
- Lubricant – Thin film of light oil or grease to help seal gasket to flange and orifice plate.
- Tachometer – Tachometer is used to determine pump speed (RPM) if not known.
- Thermometers – Thermometers are required to measure seal water temperature. A magnetic mount type temperature gauge may be necessary to measure the seal water temperature.

Pump preparation for test

1. Determine if a “single plate” or “dual plate” test is to be performed. A single plate test is performed using one test plate placed on the inlet of the pump suction manifold. A dual plate test is performed using a test plate placed directly on each of the two vacuum pump suction flanges. Figure 3 shows the test set-up for the “single plate test”. Figure 4 shows the test set-up for the “dual plate test”. Whenever possible, dual plate tests are recommended so each end of the pump can be evaluated independently.
2. Remove the necessary piping required to perform the test. If piping is lifted upward from and supported above the flange(s) being tested, at least 610 mm (24 in.) above the flange should be allowed for the test. CAUTION: Carefully secure all loose piping that is removed.
3. Carefully inspect the following areas for debris and clean if necessary. Clogging in these areas will affect the test results.
   - pump or suction manifold inlets
   - seal water piping and flow control devices near pump
   - vacuum gauge taps located on pump suction or inlet manifold
   - discharge manifold or discharge separator/silencer water drain
4. Thoroughly clean the pump inlet flanges or suction manifold inlet flange.
5. Lubricate the flange(s) evenly applying a thin coating of gasket lubricant.
6. Place specified rubber gasket(s) on inlet flange(s).
7. Lubricate the rubber gasket(s), again evenly applying a thin coating gasket lubricant.
8. Place specified orifice plate(s) upon rubber gasket(s) and apply hand pressure to ensure a tight seal is formed between the flange, gasket, and plate.
9. For single plate test, remove plug that is tapped into inlet manifold. For a dual plate test, remove one plug from each inlet.
10. Install pipe fittings necessary to fit the vacuum gauge(s) to the tapped holes. The pipe fittings must be installed so the vacuum gauges will be mounted in a vertical position (see Figures 3 and 4). Minimum piping length and elbows should be used to prevent vacuum losses. Prepare all pipe threads with PTFE tape or paste.
11. Mount the vacuum gauge(s) in a vertical position to the pipe fittings as shown in Figure 4. Prepare all threads with PTFE tape.
12. Install a thermometer or temperature gauge in or on the seal water supply piping to measure the seal water temperature during the test.

Test procedure

All testing data should be recorded on the “Vacuum Pump Data Test Sheet” located in Appendix C.

1. Open the seal water supply valve and ensure that there is adequate seal water flow to the pump. Check the installation, operation, and maintenance manual to determine nominal seal water flow for the pump. For this all seal water should go to the pump body. Water to showers in pump inlet piping should be shut off to duplicate factory test conditions.
2. With all the orifice holes open, start the pump.
3. Adjust the seal water flow with a regulating valve to stabilize the vacuum at the highest obtainable vacuum level. Maximum stable vacuum will be achieved when the needle of the analog gage holds steady without fluctuations. Increasing the water flow above this maximum stable flow will only send this extra water out
the discharge and requiring more power. After each stopper is added to the plate adjust the seal water flow again. It will be noted that less water is needed for low vacuum and more water is needed for higher vacuum. This is due to more water piston force is needed to prevent Vaneslip at higher vacuum levels. Allow time for the flows and vacuum levels to stabilize for each vacuum level data collection before proceeding to step 4.

4. If the vacuum reading is at, or above, the lowest curve vacuum level plotted on the pump’s marketing curve, record on the data sheet the vacuum level(s) and the number of open orifice holes.

5. If the vacuum reading is NOT at or above the lowest curve vacuum level, install one stopper into the orifice plate(s) and read the vacuum level. Repeat until the minimum curve vacuum level is achieved.

**NOTE 1:** For dual plate tests, take data with the same quantity of orifice holes open on each end of the pump.

6. Repeat step 3.

7. Record the vacuum level(s) and the number of orifice holes open. Record on vacuum pump data test sheet (Appendix C).

8. Continue installing stoppers and adjusting seal water for each data point. Record the open holes and vacuum levels for each data point until one hole is open (for each inlet) or until the maximum curve vacuum level is achieved. **Never plug all orifice holes.** This will starve the pump of needed air flow and could cause damage.

9. Measure pump speed (rpm) with tachometer.

10. Record seal water temperature and barometric pressure.

11. Shut pump off.

12. Shut seal water supply off.

In order to qualify the recorded test results data, it is very important to verify, with a tachometer, the rpm that the pump is running to compare to the speed lines given on the manufacturer’s performance curves.

**Calculations**

Record calculations on vacuum pump data test sheet (Appendix C).

1. Using Equation 1, correct recorded test vacuum levels for barometric pressures other than standard {760 mm, (29.92 in.) HgA}.

   **Equation 1:**

   \[ V_c = 760 \times V_t / P_b \]

   or

   \[ V_c = 29.92 \times V_t / P_b \]

   where:

   \[ V_c = \text{correct vacuum levels, mm HgV (in. HgV)} \]

   \[ V_t = \text{recorded test vacuum levels, mm HgV (in. HgV)} \]

   \[ P_b = \text{barometric pressure, mm HgA (in. HgA)} \]

2. Refer to Figures 10-17 in Appendix B. For the specified orifice hole size, record the m³/hr./Orifice (ACFM/Orifice) \(Q_{oi-idle end}, Q_{oi-drive end}\) for each corrected vacuum level \(V_c\).

3. Refer to Figure 17. For each corrected vacuum level, record the seal water correction factor \(W_{ci-idle end}, W_{cd-drive end}\).

4. For each end of the vacuum pump, using Equation 2 and Equation 3, calculate the total m³/hr (ACFM) tested \(Q_{i-idle end}, Q_{d-drive end}\).

   **Equation 2:**

   \[ Q_i = H_i \times Q_{oi} \times W_{ci} \]
Equation 3:

\[ Q_d = H_d \times Q_{od} \times W_{cd} \]

where:

- \( H_i \) = number of holes open on idle end
- \( Q_i \) = m³/hr (ACFM) tested through idle end
- \( H_d \) = number of holes open on drive end
- \( Q_d \) = m³/hr (ACFM) tested through drive end

5. Using Equation 4, calculate the total tested m³/hr (ACFM) \( Q_t \) for each vacuum level.

Equation 4:

\[ Q_t = Q_i + Q_d \]

where:

- \( Q_t \) = total pump capacity, m³/hr (ACFM)

NOTE 2: See Table 1 for SI metric conversion factors.

<table>
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<th>Table 1. Conversion factors for SI Units</th>
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<td><strong>Quantity</strong></td>
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<tr>
<td>Volume</td>
</tr>
<tr>
<td>Length</td>
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<tr>
<td>Pressure</td>
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</table>

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Add to & Multiply by

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<th>Temperature</th>
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<th>-32 x 0.556</th>
<th>degrees Celsius, C</th>
</tr>
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</table>

Result of the orifice test method

Figure 5 shows the results of the orifice test method comparing the tested airflow (dashed curve) entering the pump to the original airflow (solid curve). Note that the percent difference becomes greater for higher vacuum levels. This is due to more vaneslip when the pressure differential increases between the discharge pressure (slightly higher than atmospheric) and the lower inlet pressure (higher vacuum). Note that the consumed horsepower with less than original airflow is the same as original since the pump is compressing the same volume as original (with vaneslip recirculating with every revolution).
Alternate methods of air flow measurements

Air flow measurement using a pitot tube

A pitot tube can be inserted in the vacuum pump inlet piping through a relatively small drilled hole that can be later plugged. Measurements can be made without dismantling the piping making this procedure relatively simple and fast to perform. Once ports are installed repeating the tests at periodic intervals will provide data that trends performance over time.

The accuracy of pitot tube air flow measurements is dependent on piping configuration and stability of the air flow. It requires enough straight length of pipe to insure stable air flow at the point of measurement. That said, repeated measurements taken at the same location following the established procedure will provide a reliable performance trend.

This method uses a small diameter pitot tube inserted through a hole in the side of the vacuum pipe to obtain a velocity profile. This method can be done on the fly and is reasonably unobtrusive: only a single hole large enough to admit the pitot tube is required in the vacuum line. There are some caveats:

1. To assume laminar flow, 10 pipe diameters of straight run before the measurement point and 5 diameters after are nominally required. This condition is seldom found, with consequent error in measurement.
2. Such measurement error can generally be assessed by the stability of the velocity head measurement. If the head is stable, the flow is probably reasonably laminar. If it varies wildly, it is probably turbulent.
3. Two-phase flow can really compromise the measurement, too, and such flow is common to vacuum pumps.
4. When velocity gets very high, friction in the line goes up but the effect can be mitigated by mapping velocities over a grid across the pipe diameter.

Air flow measurement with hot wire anemometer

Hot wire anemometers use a fine wire electrically heated to some temperature above ambient. Air flowing past the wire has a cooling effect on the wire. As the electrical resistance of most metals is dependent upon the temperature of the metal, a relationship can be obtained between the resistance of the wire and the flow speed.

This procedure is similar to the pitot tube method where the anemometer would be inserted through a small hole in the side of a straight run of vacuum pipe to obtain a velocity profile. However, hot wire anemometers are very sensitive to moisture or particulate in the air stream. They would not be suitable for taking measurements under machine operating conditions.

Pump evaluation using fiber optic inspection

Fiber optic inspection (Borescope or Boroscope) does not provide an air flow measurement rather it provides a picture of pump internals which with experience can provide a subjective estimation of loss of pump performance.

1. It is fast and relatively easy to perform during a short outage. It only requires that the equipment be locked out.
2. It will show areas of wear or erosion/corrosion damage in critical sealing areas of the pump. It will also show areas where there is a build-up of scale or contaminants that may result in loss of capacity.
3. If a fiber optic inspection does not reveal any significant deficiencies but pump performance appears to be low, then other areas of the system should be more closely scrutinized.
4. If inspection indicates severe scale or fouling, then a chemical cleaning should be performed.
5. If there are indications of mechanical deficiencies, erosion or corrosion damage, excessive clearances, etc., then a flat plate orifice test should be performed to more accurately evaluate the loss of capacity compared to new pump performance curves before undertaking the cost of rebuild or replacement.

Examples of fiberoptic inspections are included in Appendix D.

Summary

Field testing vacuum pumps has many benefits. The flat-plate orifice test method is the most reliable way to show pump capacities for the entire range of vacuum levels. Having the ability to field-test vacuum pumps enables mill personnel to make critical decisions about their vacuum systems. Production is directly affected by vacuum and inefficient vacuum pumps are often bottlenecks for paper machines. Replacing inefficient pumps will not only eliminate such bottlenecks, but also reduce wasted energy, water, and dryer steam costs. Vacuum system troubleshooting can be made easier with the orifice test method. By testing the vacuum pump of a troubled system while isolated from the process, problems can be determined to be either pump or system problems. Once the problem is determined, locating the root cause will be simpler.

Related TIPs that address airflow at vacuum

1. TIP 0404-47 Paper machine performance guidelines
2. TIP 0404-27 Press fabric dewatering and conditioning - suction box (Uhle box) design and vacuum requirement
3. TIP 0404-55 Performance evaluation techniques for paper machine vacuum systems
4. TIP 0404-60 High vacuum sheet dewatering
5. TIP 0404-63 Paper machine energy conservation
6. TIP 0502-01 Paper machine vacuum selection factors

Keywords

Air flow, Vacuum pumps, Sealants, Water, Openings, Test methods

References


Additional information

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Working Group:
Robert “Bob” Matzka, PE – Chairman, MEGI Engineering, Inc.
Charles H. Wunner, Vooner FloGard Corporation
John A. Neun, PE, John A. Neun, LLC
Bob Kinstrey, Jacobs Engineering
Mark Phiscato, Essity International
Tom Dardis, Gardner Denver Nash, LLC
Appendix A. Orifice plates and gasket layouts

Figures 6, 7, and 8 show, respectively, layouts A, B, and C. Figure 9 shows the rubber gasket schematic.

**Figure 6. Layout A**

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<tr>
<th>Flange Diameter (in)</th>
<th>D1 (in)</th>
<th>D2 (in)</th>
<th>D3 (in)</th>
<th>Thickness* (in)</th>
<th>Hole Diameter (in)</th>
<th>Angle Offset R1</th>
<th>Angle Offset R2</th>
<th>Number of Holes in R1</th>
<th>Number of Holes in R2</th>
<th>Weight (lbs)</th>
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*Thickness to resist full vacuum (29.92"HgV) with a minimum Safety Factor of 1.5
Orifice hole diameters are to be ±0.002" with clean, sharp, square edges.
ASME A36 Low Carbon Steel

**Figure 7. Layout B**
**Figure 8.** Layout C. Note: Thickness to resist full vacuum (29.92 in. HgV) with a minimum safety factor of 1.5. Orifice hole diameters are to be ±0.0002 in. with clean, sharp, square edges. ASME A36 low carbon steel.

**Figure 9.** Rubber gasket schematic
Appendix B. Volumetric flow rates

Figures 10-17 show the volumetric flow rates of atmospheric air through a reamed orifice hole in ¼ in thick plates.

**Figure 10.** Volumetric flow rate of atmospheric air through a reamed orifice hole in a 6.35 mm (0.250 in.) thick steel plate. The hole diameter is 9.53 mm (0.375 in.). The air conditions are standard: barometric pressure = 760 mm Hg (29.92 in. HgA); temperature = 15.6°C (60°F).

**Figure 11.** Volumetric flow rate of atmospheric air through a reamed orifice hole in a 6.35 mm (0.250 in.) thick steel plate. The hole diameter is 12.7 mm (0.500 in.). The air conditions are standard: barometric pressure = 760 mm Hg (29.92 in. HgA); temperature = 15.6°C (60°F).
Figure 12. Volumetric flow rate of atmospheric air through a reamed orifice hole in a 6.35 mm (0.250 in.) thick steel plate. The hole diameter is 15.9 mm (0.625 in.). The air conditions are standard: barometric pressure = 760 mm Hg (29.92 in. HgA); temperature = 15.6°C (60°F).

Figure 13. Volumetric flow rate of atmospheric air through a reamed orifice hole in a 6.35 mm (0.250 in.) thick steel plate. The hole diameter is 19.1 mm (0.750 in.). The air conditions are standard: barometric pressure = 760 mm Hg (29.92 in. HgA); temperature = 15.6°C (60°F).
Figure 14. Volumetric flow rate of atmospheric air through a reamed orifice hole in a 6.35 mm (0.250 in.) thick steel plate. The hole diameter is 25.4 mm (1.00 in.). The air conditions are standard: barometric pressure = 760 mm Hg (29.92 in. HgA); temperature = 15.6°C (60°F).

Figure 15. Volumetric flow rate of atmospheric air through a reamed orifice hole in a 6.35 mm (0.250 in.) thick steel plate. The hole diameter is 31.8 mm (1.25 in.). The air conditions are standard: barometric pressure = 760 mm Hg (29.92 in. HgA); temperature = 15.6°C (60°F).
Figure 16. Volumetric flow rate of atmospheric air through a reamed orifice hole in a 6.35 mm (0.250 in.) thick steel plate. The hole diameter is 38.1 mm (1.50 in.). The air conditions are standard: barometric pressure = 760 mm Hg (29.92 in. HgA); temperature = 15.6°C (60°F).

Figure 17. Seal water corrections for temperature for cone ported liquid ring vacuum pumps (Wci, Wcd). Corrected to standard 15.6°C (60°F) seal water temperature.
Appendix C. Vacuum pump data test sheet

**VACUUM PUMP DATA TEST SHEET**

**MILL:**

**LOCATION:**

**DATE OF TEST:**

**PERFORMED BY:**

**APPLICATION:**

**PUMP SPEED:**

- Nameplate:
- Tachometer:

**PUMP EQUIP. No.:**

**PUMP TEST No.:**

**PUMP MODEL:**

*Pb: BARO. PRES.; mm HgA (in. HgA):

S. WATER TEMP; °C (°F):__

**ORIFICE HOLE DIAM.; mm (in.):**

**MOTOR DATA**

- Speed:
- H.P.:
- Full Load Amps:

<table>
<thead>
<tr>
<th>Vacuum</th>
<th># of Orifice Holes Open</th>
<th>Corrected Vac. mm (inch) HgV</th>
<th>Flow Per Orifice Cu. m/h (ACFM)</th>
<th>Seal Water CF</th>
<th>Seal Water CF</th>
<th>Flow Tested</th>
<th>Flow Tested</th>
<th>Total Flow</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Drive</td>
</tr>
</tbody>
</table>

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*Note:* The table above is a vacuum pump data test sheet with fields for various measurements and conditions related to the performance of the liquid ring vacuum pump. It includes sections for identifying the mill and location, the date of test, the person performing the test, the pump equipment number, and the pump test number. The sheet also includes a section for motor data, which includes speed, horsepower, and full load amps. The main table includes columns for vacuum measurements, number of orifice holes open, corrected vacuum, flow per orifice, seal water flow, seal water flow tested, and total flow. The rows correspond to different conditions such as idle and drive, with specific values for each condition.
Appendix D. Examples of fiberoptic inspections

Drive end rotor clearance – normal

Driven end port – est. 80% blockage

Fixed end rotor clearance – normal

Fixed end rotor port – est. 30% blockage

Drive end rotor to body – increased clearance

Major wear on center shroud area
Rotor to cone clearance in fair condition with some pitting

Rotor to body clearance wider than normal and in fair condition

Body on poor condition with heavy erosion and wear

Body on poor condition with heavy erosion and wear