Proceedings of The South African Sugar Technologists' Association — June 1986

MEASURING VACUUM PUMP PERFORMANCE

By R. A. H. CHILVERS and D. J. LOVE

Tongaat Hulett Sugar Limited - Felixton

Abstract

A simple reliable method of measuring vacuum pump performance by using a test manifold with a series of critical flow orifice plates is described. The factors which affect vacuum pump performance, are discussed. In addition the equations needed to size the orifice plates for a given flow are given, together with details of the test manifold.

Introduction

In any sugar mill, vacuum pumps play a major role in the production of sugar. Vacuum technology is used wherever boiling is required at temperatures below 100°C and in addition is used for the removal of filtrate from muds as well as to dewater smuts.

In most applications vacuum pumps are used in conjunction with condensors. The condensor is used to condense vapour produced while the vacuum pumps are used to remove the incondensible gases. Poor vacuum pump performance usually results in inferior process results being achieved. For this reason it is important to be able to easily and quickly identify the cause of the out of spec operation.

At Felixton a total of 15 vacuum pumps are used throughout the plant. Over the past two years there have been numerous failures particularly on the pumps used on the pans. It thus became essential to be able to determine accurately whether or not a vacuum pump was performing properly.

An investigation was conducted into the various vacuum pump test methods available and as a result of this investigation the following facts emerged:

- The closed valve test does not give a good indication of pump condition.
- Any meaningful test must relate the quantity of air handled by the pump to the vacuum produced.
- The ideal test would enable the pump performance to be compared with the manufacturers data.
- Any test adopted must be simple enough for a section artisan to carry out.

After careful examination of the Nash method of measuring vacuum pump performance curves it was recognised that in its published form it would not be suitable for on plant testing of vacuum pumps for the following reasons:

- The test rig required numerous different sets of orifice plates.
- Numerous graphs and corrective factors are needed to produce the pump curve.
- The procedure is too complex and time consuming for a section fitter.

Despite the disadvantages of the Nash method, it was felt that if the test rig and the analytical and graphical methods used by Nash could be simplified, then it would be possible to produce pump curves easily on site.

The paper describes the various topics in the following sequence:

- **Pump Curves** – a brief description of factors affecting vacuum pump curves will be given.
- **Simplification of Analytical data.**
  Critical flow orifice plates are discussed and the equation relating gas flow to orifice size at a given pressure is given.
- **Description of test unit.**
  The test unit is described together with drawings and relevant data.
- **Test procedure.**
  The test procedure is described together with actual results which have been obtained.
- **Operational Performance.**
  The experience gained while using this method of testing vacuum pumps is discussed.

Pump Performance Curves

In testing a vacuum pump it is important to remember that the vacuum pump forms only part of the whole system.

In most cases the only definite fact available is that the absolute vacuum required is not being achieved. Invariably the vacuum pump is blamed. It is thus imperative to have some reliable test which can be used to determine if in fact the pump is healthy or not.

The most reliable method of testing any pump is to plot its performance curve. Since the liquid ring vacuum pump is essentially a positive displacement pump (expressed in terms of inlet flow) it is obviously no exception.

With these thoughts in mind it was felt that if a reasonably accurate performance curve could be plotted then the following benefits would apply:

- The pump could be compared with manufacturers curves.
- It would enable accurate estimates of air loading vs pressure to be made which would help in isolating leaks etc.
- The shape of the curve could be used as an indication of the type of damage which had occurred in the pump.
- It would provide an independent test which would satisfy process and engineering staff.

In order to produce a vacuum pump performance curve it is necessary to measure the absolute pressure as a function of air flow handled by the pump.

In order to be able to do a true evaluation of pump performance it is necessary to eliminate (or quantify) all outside factors which could affect the pump performance curve.

Atmospheric Pressure

Pump performance will be affected by atmospheric pressure. For this reason any curves plotted at pressures which are different from those used by the manufacturer will result in slightly different results. With a relative increase in atmospheric pressure, the pump performance will appear to be decreased slightly. For most cases this effect is not significant and it can be compensated for if necessary.

Atmospheric Temperature

There is a small effect on pump curves due to atmospheric temperature mainly as a result of the change in air density with different temperature. This can be corrected for, if there is a significant relative difference but generally its effect can be neglected.

Cooling Water Temperature

The maximum possible vacuum obtainable will be dependent on the vapour pressure of the cooling water. For vacuum pumps operating close to the vapour pressure of the cooling liquid (P_{cw}) it will be found that most of the vacuum pump work is done in removing the vapour produced by the flashing cooling water. Since there are localised low pressure regions within the heart of the pump flashing will take place a few kPa before the theoretical max vacuum and hence the practical maximum vacuum obtainable (P_{abs}) is:

$P_{abs} = P_{cw} + \Delta P$ where ΔP will vary depending on the actual design of pump used.

The effect of cooling water temperature can be seen from Table 1 and this effect must be taken into account.

The exact de-rating factors will depend on the type of liquid ring vaccum pump used and this information should be obtained from the manufacturer.

Efficiency of Pump

There are many factors which will affect the efficiency of a vacuum pump namely:

- Inlet and outlet seals - If seals are worn bypassing results and the efficiency of the pump is affected. This is the most common cause of reduced performance.
- Incorrect metering of cooling water - If too much water is used then the pump will be overloaded. If too little water is used, the temperature of the liquid ring can rise and pump seizure can result.
- Air leaks - Any air leaks will obviously adversely affect the ability of the pump to do useful work.
- Outside influences - Pump efficiency can also be adversely affected by pump back pressure.
- Other influences - There are numerous other small factors which can affect pump efficiency but usually it is not necessary to locate the exact cause of failure as it is normally sufficient to know the pump is operating inefficiently.

Table 1

The effect of cooling water temperature on the capacity of a rotary vacuum pump relative to water temperature.

Vacuum (kPa)	Temperature 15°C	20°C	25°C	30°C	35°C
70	1	0,98	0,95	0,91	0,86
75	1	0,98	0,94	0,89	0,83
80	1	0,97	0,92	0,86	0,78
85	1	0,96	0,89	0,81	0,71
90	1	0,94	0,83	0,71	0,55
92,3	1	0,92	0,78	0,62	0,41

"capacity" not performance relative to water temperature of 15°C

Table 2

Orifice Diameter (mm)	Orifice Area (mm²)	P_2 Downstream Pressure (kPa abs)	Q_2 Downstream Volumetric Flow (m³/s)	C Discharge Coefficient
12,7	126,7	33,60	0,0623	0,824
12,7	126,7	9,89	0,209	0,814
9,5	71,3	20,05	0,0585	0,823
9,5	71,3	6,50	0,179	0,818
1,59	1,98	20,05	$1{,}60 \times 10^{-3}$	0,811
1,59	1,98	6,50	$4{,}91 \times 10^{-3}$	0,806

Table 3

Conversion factor (K) for selected downstream gauge pressures.

Downstream Gauge Pressure (kPa)	Downstream Absolute Pressure* (kPa)	Conversion Factor (k*) (mm²/m³/min)
-70	31,3	31,8
-75	26,3	26,7
-80	21,3	21,6
-85	16,3	16,6
-90	11,3	11,5

* Assuming an atmospheric pressure of 101,3 kPa.

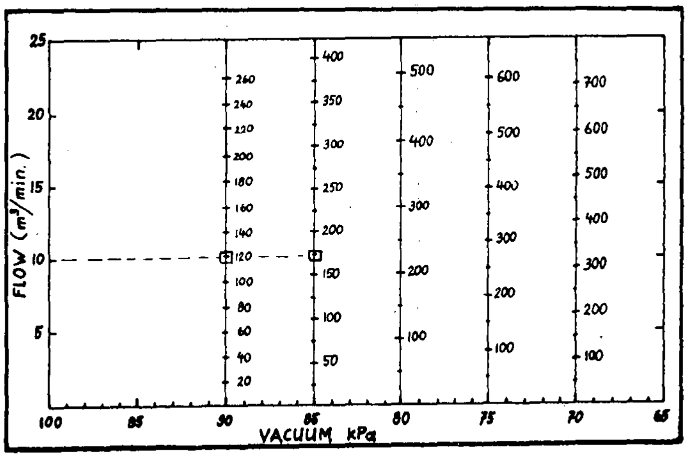


FIGURE 1 Fig 1 shows a series of scales which relates orifice area to air flow in m³/min at the vacuum pressures. e.g. a 120 mm² orifice at 90 kpa and 175 mm² orifice at 85 kPa will both relate to an air flow of 10 m³/min.

Simplification of Analytical Data

There were three major simplifications made to the Nash approach.

- While testing it was assumed that the open area of orifice holes would be adjusted to give finite pressure readings.
- The means of converting orifice size to air flow was considerably simplified.
- The test rig was simplified by sizing the holes in a binary sequence.

Critical Flow Orifices

Under normal conditions the flow of a gas through an orifice depends on both the upstream and downstream conditions. However as the downstream pressure is reduced, a point is eventually reached where sonic velocity is achieved through the orifice.

This is known as critical flow and the flow rate through the orifice is essentially independent of any further decrease in downstream pressure. For air flow through orifices (with $B < 0{,}2$) critical flow occurs when the downstream pressure is 52,8 % of the upstream pressure (in absolute units).

Perry[1] gives the following equation for critical flow (with $B < 0{,}2$)

$$W = CA\sqrt{P_1 R_1 k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} \quad \ldots\ldots (1)$$

But for air k = 1,4
Simplifying (1)

$$W = CA\sqrt{0{,}469\,P_1\,R_1} \qquad \ldots\ldots (2)$$

However what is of interest in testing vacuum pumps is the downstream volumetric flow, Q, as a function of downstream pressure, P_2.

$$Q_2 = W/R_2 \qquad \ldots\ldots (3)$$

and $R_2 = P_2R_1/P_1$ (assuming no change in temperature) (4)
Substitute (4) into (1) and combining with (3).

$$Q_2 = \frac{CA}{P_2}\sqrt{\frac{0{,}469\,(P_1)^3}{R_1}} \qquad \ldots\ldots (5)$$

The unknown quantity in the above equation is the discharge coefficient C.

The Nash Engineering Company present graphical data on air flow through orifices for their design of vacuum pump test unit.[2] Table 2 gives values of C calculated for a number of data points selected from the Nash information.

The Nash data is all based on the following conditions:

Upstream Pressure, $P_1 = 1{,}013 \times 10^5$ Pa
Temperature, T = 15,56°C
$\therefore$ Upstream Density, $R_1 = 1{,}223$ kg/m^3

Substituting P_1 and R_1 into equation (5) we get:

$$C = \frac{Q_2P_2}{2{,}0} \cdot 10^7 \cdot A \qquad \ldots\ldots (6)$$

It is clear from the table that the discharge coefficient remains constant over the range of downstream pressures (P_2) and orifice sizes (A) considered. An average value of C = 0,82 can thus be assumed.

Substituting this into equation (6) and re-arranging gives:

$$Q_2 = \frac{1{,}64.10^7.A}{P_2} \qquad \ldots\ldots (7)$$

for the given upstream conditions.

It is then possible to calculate factors for a number of specified test pressures which will convert orifice area into volumetric flow at the pump suction, as in Table 3.

Once (K) is found which gives the ratio of orifice area to air flow in m^3/min, then it is relatively simple to calibrate a series of scales which will directly relate orifice area to air flow in m^3/min as is shown in Figure 1 below.

Description of Test Unit

A detailed drawing of the test unit can be seen in Figure 3. The unit consists of two rows of 5 orifice plate holders mounted at approximately 90° to one another. These 25 mm ID holders are welded to 150 mm diameter pipe, 350 mm long.

The one end of the 150 mm pipe is open and flanged. The other end is blocked but contains a socket for the vacuum guage.

The first five orifice plates installed in the holder are sized to give air flow quantities which increase by a factor of two between successive holders. The remaining five are a constant diameter.

This sizing of orifice plates can be seen in Figure 2 below.

It is important to note that the most critical portion of the test rig is the orifice plate itself.

These plates must be as detailed by Nash or the discharge coefficients will not be exactly as specified.

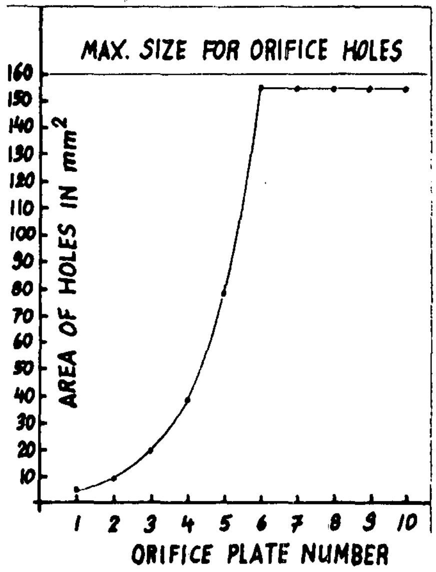


FIGURE 2 Sizing of orifice plates

If the Nash specification is followed exactly an error of less than 2 % can be expected.

Nash[2] (pg 2) specify: "The orifices are made of hardened stainless steel plates or equivalent, ground to a uniform thickness of 1/8 inch. The holes through these orifice plates are reamed to size, extreme care being taken to ensure a sharp, square edge. It is essential that the sharpness of this edge be maintained otherwise accuracy of the results cannot be guaranteed".

In practice we have found that reasonable results can be obtained by manufacturing these orifice plates from standard 1/8 plate inch and by just drilling the holes of the required diameter. The area of the hole is the most important factor.

For the test to be effective it is more important to ensure repeatability and reliability than absolute accuracy.

Test Procedure

Use of a test rig

In order to test a vacuum pump the following sequence is followed:

(1) First the cooling water temperature, atmospheric temperature and pressure is obtained and recorded on the pre-printed sheet (see Fig (4)) together with all relevant pump data.

(2) The test unit is then bolted onto the pump. Care is taken to ensure that there is a good seal between pump and test unit.

(3) The pump is isolated so that only air flowing through the test unit will enter the pump.

(4) The pump is then started with all orifice holes closed. The seal across the orifice plates is done by using small rubber disks. (30 mm diameter × 3 mm thick).

(5) Once the pump has run up to temperature and equilibrium is reached, the test is then started.

(6) The rubber flaps across the orifice plates are then removed or added until the required vacuum is measured on the pressure gauge. (These pressures are marked on the test sheet). The number of open holes are then marked down on the sheet in the correct column.

(7) This procedure is repeated for all vacuum readings shown on the sheet.

(8) Once all the readings have been obtained as marked on the sheet, it is a simple matter of addition to add up the columns and obtain the area of orifice plates used to obtain each pressure reading. These areas are then directly plotted on the pre-printed sheet and a pump performance curve is produced. Alternatively equation (5) could be used to calculate Q_2 directly.

(9) The manufacturers pump curve together with the general effect of cooling water temperature on pump performance is also shown on the sheet. It is then a very simple matter to decide if the pump is faulty or not.

Operational Performance

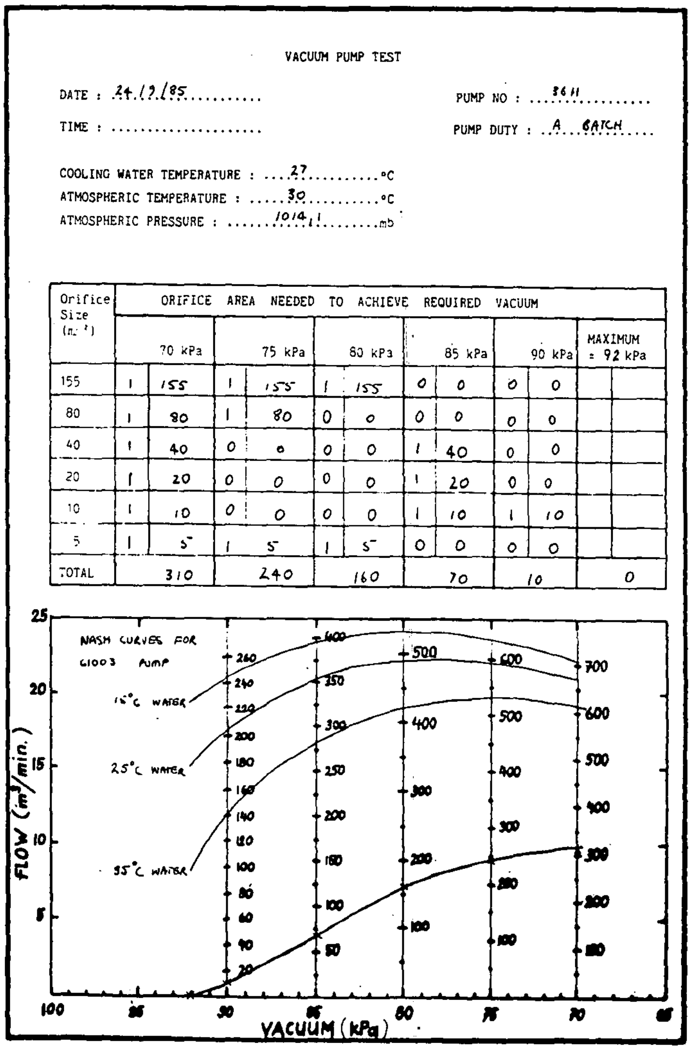
This method of testing vacuum pumps was perfected near the beginning of the 1985 season. It has been successfully used since then to isolate a number of faulty pumps.

The test method used has eliminated the "art" of vacuum pump testing and made it an exact science.

In addition to isolating pumps which are not performing properly, the test has also been used effectively to:

- Establish that the closed valve test (zero flow) is not a good test of pump condition.
- Determine the effect of back pressure on the vacuum pump performance.
- Determine the amount of air leakage which is taking place on piping and vessels.

This method of testing has been totally accepted as a true test of pump condition by the engineering and process departments. The complete test is carried out by the section fitter and all tests are recorded in the planned maintenance system. It is felt that in time we will be able to predict the cause of pump failure by examining the shape of the performance curve.



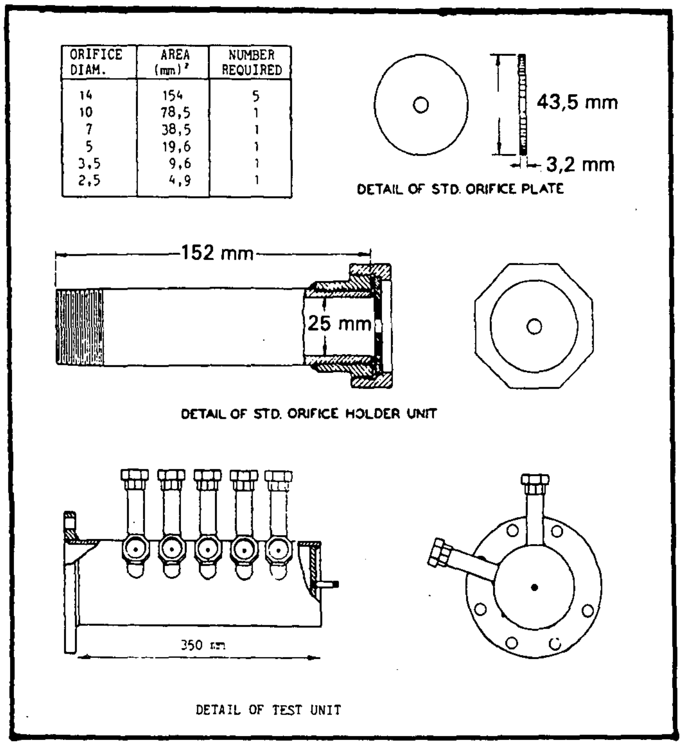
VACUUM PUMP TEST

DATE : 24.12.85
TIME :
PUMP NO : 36 11
PUMP DUTY : A BATCH

COOLING WATER TEMPERATURE : 27 °C
ATMOSPHERIC TEMPERATURE : 30 °C
ATMOSPHERIC PRESSURE : 1014,1 mb

Orifice Size (mm^2)	ORIFICE AREA NEEDED TO ACHIEVE REQUIRED VACUUM											
	70 kPa		75 kPa		80 kPa		85 kPa		90 kPa		MAXIMUM = 92 kPa	
155	1	155	1	155	1	155	0	0	0	0		
80	1	80	1	80	0	0	0	0	0	0		
40	1	40	0	0	0	0	1	40	0	0		
20	1	20	0	0	0	0	1	20	0	0		
10	1	10	0	0	0	0	1	10	1	10		
5	1	5	1	5	1	5	0	0	0	0		
TOTAL	310		240		160		70		10		0	

FIGURE 4



ORIFICE DIAM.	AREA (mm)^2	NUMBER REQUIRED
14	154	5
10	78,5	1
7	38,5	1
5	19,6	1
3,5	9,6	1
2,5	4,9	1

FIGURE 3

Conclusions

- The condition of a vacuum pump can be accurately determined by examining its performance curve.
- Plotting a vacuum pump performance curve can be made very simple as is shown in this paper.
- The operating point of the vacuum pump can be compared with its design setpoint.
- The test rig and equations described can be used for any type of vacuum pump.
- The ability to plot the performance curve enables many of the factors such as temperature, back pressure and air leakage, which affect vacuum pump performance, to be evaluated accurately.

REFERENCES

1. Perry RH and Chilton CH, 1973. *Chemical Engineers Handbook*, 5th Ed., McGraw Hill, New York.
2. Adams HE, *Accurate Air Measurement by Nash Orifice Method*, Nash Engineering Company, Norwalk.
3. Rynas JL and S Croll, (1981) Selecting Vacuum Systems, *Chemical Engineering*, December 14.

NOMENCLATURE

A	Area of orifice (m^2)
B	Ratio of orifice diameter to pipe diameter.
C	Discharge coefficient of orifice
k	Ratio of specific heats
P	Pressure (Pa)
Q	Volumetric flow rate (m^3/s)
R	Density (kg/m^3)
T	Temperature (°C)
W	Mass flow rate (kg/s)
K*	Conversion factor relating flow to area of orifice ($mm^2/m^3/min$)

Subscripts

1. Upstream conditions
2. Downstream conditions