DESIGN CONSIDERATIONS AND APPLICATION GUIDELINES FOR PUMPING LIQUIDS WITH ENTRAINED GAS USING OPEN IMPELLER CENTRIFUGAL PUMPS

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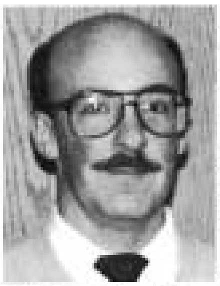

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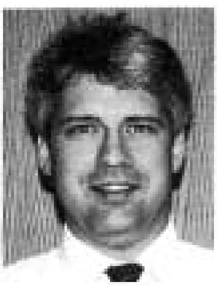
Mr. Cappellino received a B.S. degree in Mechanical Engineering from Clarkson College of Technology and is a member of ASME.



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ABSTRACT

The proper selection of a centrifugal pump for liquid and gas (two phase) mixtures, is highly dependent on the amount of gas and the characteristics of the mixture. The presence of entrained gases will reduce the output of centrifugal pumps and can potentially cause loss of prime. Conventional pump designs can be used for low percentages by volume (up to four percent), while special impeller modifications are used effectively to handle five percent to 10 percent gas by volume, although performance corrections are required for proper pump selection. Pump performance test data is presented for low to medium specific speed pumps (900 to 3000 U.S. units), pumping water with up to 10 percent entrained air. The results are shown for conventional pumps and those modified for air handling. Also discussed are the effects of suction pressure and impeller vane number. The effectiveness of inducers, vortex pumps, and special pump designs for gas extraction for up to 40 percent gas by volume are discussed. Application guidelines are presented for the proper selection of centrifugal pumps, which consider the percentage of gas volume, the pump size, system operation, impeller trim, and suction head.

INTRODUCTION

The ability to pump liquid and gas mixtures is vital to many industrial processes. Most of these applications are less than 15 percent gas by volume, while some may be as much as 40 percent or higher. Pumped mediums can range from water to complex suspensions such as paper stock. The entrained gas may be an essential part of the industrial process or may be unwanted, such as air that is entrained in the suction system due to agitation, or drawn in through vortices caused by inadequate suction submergence. The best pump performance is with zero percent entrained gas. Thus, if possible, steps should be taken to reduce the amount entrained gas through suction system design changes, gas venting systems, and baffles to prevent vortex [1]. Often the entrained gas cannot be effectively removed and, therefore, must be transported through the pump efficiently without losing prime.

Stepanoff [2] describes the positive effects of increasing pump suction pressure on gas handling capability. As the gas enters the impeller passage, the decrease in pressure on the low pressure side of the vane causes an expansion in gas volume by the ratio of the absolute pressure change. For example, if a pump operating with a suction head of 38 ft of water absolute and a pressure drop of 10 ft of water occurs at the impeller inlet, then the volume will increase by the factor of 38/28 = 1.36. If the suction head is 59 ft of water absolute, and the same 10 ft of water pressure drop occurs at the impeller inlet, then the volume will increase by the factor of 59/49 = 1.20. Thus, with higher suction pressure, less gas expansion occurs at the pump inlet and there is greater gas handling capability.

It should be noted that entrained gases can cause an increase of NPSH required by centrifugal pumps. LeFur, David, and Pecot [3] present data showing the influence of up to five percent air on NPSH performance for low specific speed pump (N_s = 1030 U.S. units), and a mixed flow pump (N_s = 4130 U.S. units). When specifying a centrifugal pump to handle entrained gases, the effect on NPSH required should be discussed with the pump manufacturer.

Liquid gas mixtures, where the gas does not condense as it passes through the pump are addressed. The effect of mixtures of steam and water on pump performance are discussed in [4, 5].

Many of these problems are typified in the pulp and paper industry. For example, a key step in recycling materials such as newspaper and magazines is deinking through flotation cells. In these cells (Figure 1), air is injected into the pulp slurry. The air bubbles promote separation of the ink from the paper fiber and the formation of an inky froth that is then skimmed off the surface. Several stages of this process are usually carried out for complete deinking. Unwanted air can be entrained many ways throughout the pulping, washing, and bleaching process such as excessive agitation, vortexes due to inadequate submergence in stock chests, poor suction piping design, and excessive air frothing in vacuum seal tanks. While the typical deinking cell has entrained air from six percent to nine percent by volume, many pumps are required to handle unwanted air in the range of four percent to six percent. Typical liquids can be clear such as clarified water, but are usually low consistency stock (one percent to six percent fiber by weight) suspension in water. Higher consistency stock (eight percent to 16 percent) can have much higher amounts of air (Figure 2) and require special designs using gas extraction devices for best operation. These large amounts of air consist of air that is trapped within the wood fibers, bound to the fibers within a floc or group of fibers and free air that is trapped between the fiber flocs. The air content is also dependent upon process conditions such as vacuum washer efficiency.

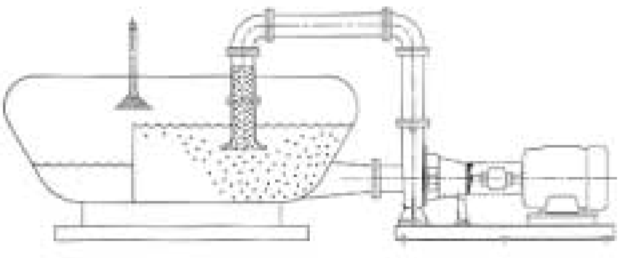

Figure 1. Typical Flotation Cell.

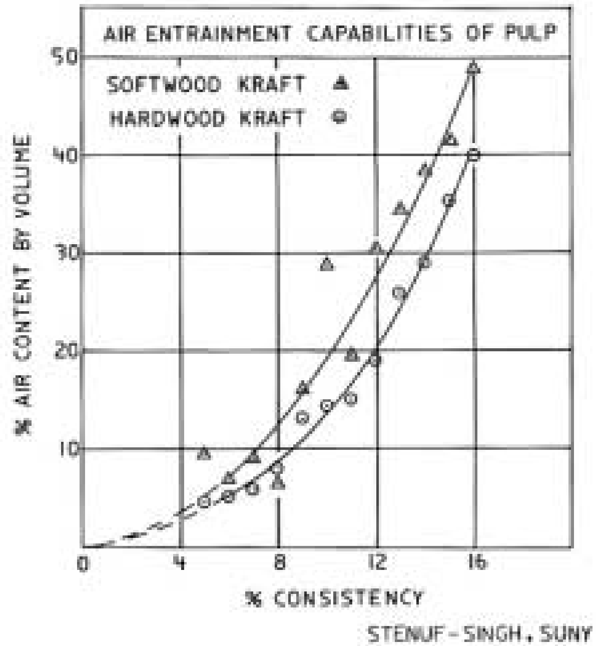

Figure 2. Typical Percentages of Air vs Stock Consistency.

Many petrochemical processes involve pumping two phase flow. Often the gas phase is created by a chemical reaction in some part of the process. The manufacture of plastics and elastomers are particularly prone to problems resulting from gas entrainment. Downhole pumps are also subject to potentially large amounts of entrained gas. The effect of entrained gas on submersible multistage pumps is described by Turpin, et al. [6], along with the positive effect of very high pump suction pressures on gas handling capability.

Virtually any type of centrifugal pump can handle some amount of entrained gas. The problem to be addressed is the tendency for gas to accumulate in the pump suction inhibiting head and flow generation. If gas continues to accumulate, the pump may lose prime [2]. Murakami and Minemura [7, 8] present photographs showing the cavities of air on the low pressure side of the blade at the impeller inlet. Test observations indicate successful pumping with a surprisingly large volume of accumulated air in the suction eye. The pressure drop at the impeller inlet causes an expansion of the entrained air bubbles. The resulting cavities close off the area available for liquid flow, and create additional hydraulic losses. Full or partially shrouded open impellers (Figure 3) can handle entrained gases more effectively than closed impellers. The leakage path across the vanes reduces the pressure drop at the impeller inlet and creates turbulence that tends to break up the air accumulation. For less than four percent gas by volume, open impellers with normal running clearances (0.015 in) are sufficient and pump performance remains efficient. As the percentage of air exceeds four percent by volume, the performance of conventional impellers begins to degrade drastically (Figure 4), until the pump becomes unstable, eventually losing prime. It has been found beneficial to increase the impeller to casing running clearance (0.090 to 0.180 in) allowing greater leakage, which more effectively prevents large accumulations of air in the pump suction (Figure 3). Murakami and Minemura [9] present test results for normal and enlarged clearances for percentages of entrained air up to 10 percent.

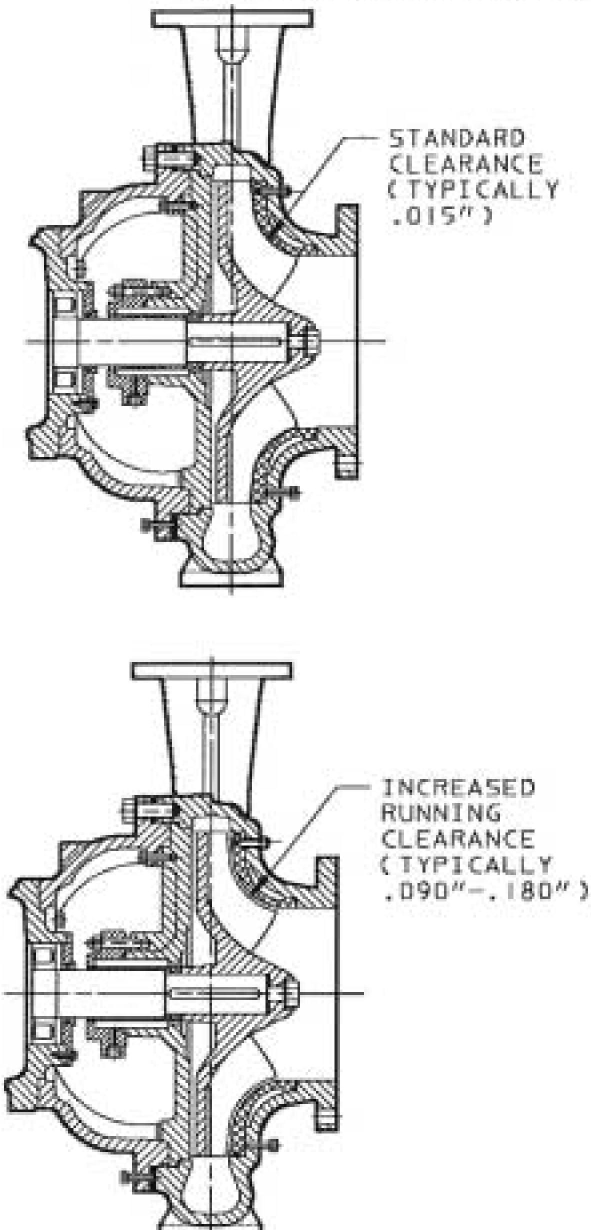

Figure 3. Open Impeller End Suction Pump with Normal Running Clearance and Increased Running Clearance.

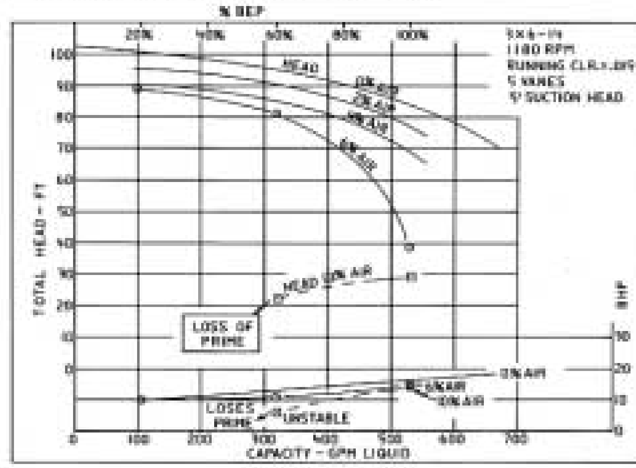

Figure 4. Head and Power vs Capacity Zero to Ten Percent Air by Volume for Normal Running Clearances.

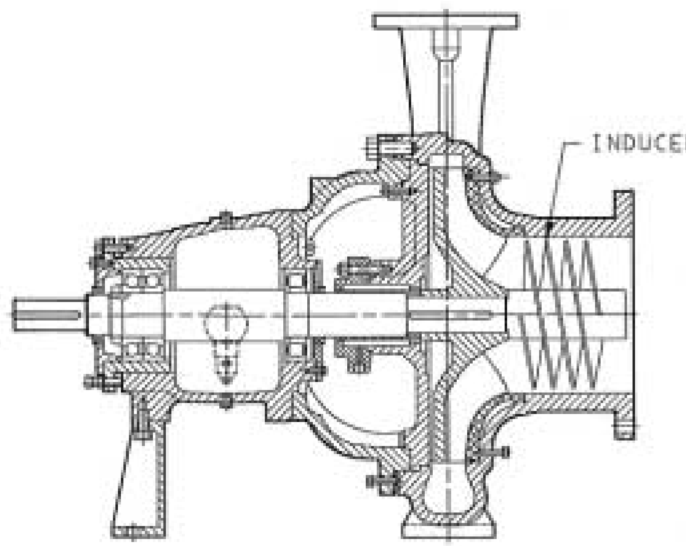

Figure 5. Open Impeller End Suction Pump with Inducer.

Data presented herein are limited to a specific speed range of 900 to 3000 (U.S. units), which covers most pumps used in the chemical and paper industry. Little variation in gas handling capability has been found in this specific speed range. Schiavello [10] reports an improvement in gas handling for higher specific speeds (5100 U.S. units).

Inducers and other devices have also been found useful in preventing air binding and enhancing air handling capabilities in centrifugal pumps. A standard open impeller pump is shown in Figure 5, equipped with an axial inducer. The inducer increases suction pressure immediately in front of the impeller leading edge, it compresses the gas reducing the volume and enhances the air handling ability of the pump.

A special purpose pump used for separating and extracting air from pumped media is demonstrated in Figure 6. It uses venting ports in the impeller hub together with a repeller and wide pumpout vanes. Air contents of up to 40 percent by volume at low (zero to ten ft) suction head have been successfully extracted by this type of pump. The air collects around the pump shaft at the eye of the impeller and is passed through the venting ports along with some of the pumped medium.

A vacuum is created behind the impeller by a liquid ring vacuum pump connected to the vacuum chamber. A specially designed repeller is situated between the impeller balance holes and the vacuum chamber to prevent the pumped medium from entering the vacuum pump.

Once the air is removed from the pumped medium, it is pumped as in an unmodified centrifugal pump without the head loss associated with air entrainment.

EXPERIMENTAL TEST PROGRAM

Purpose of Test Program

The effect of entrained gases on pump performance is very complex, involving many variables. Analytical approaches provide insight into the basic mechanisms involved in pump perform-

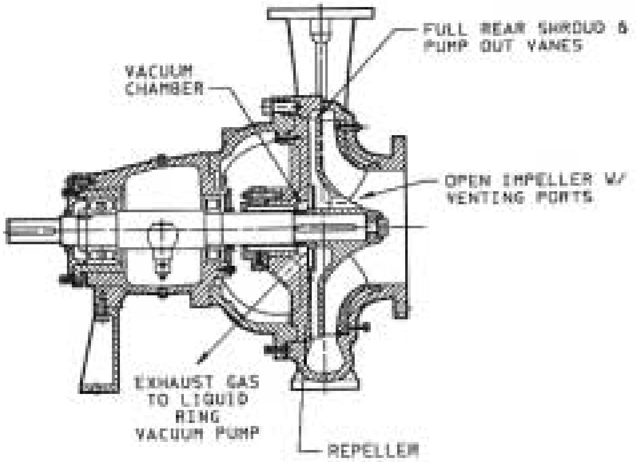

Figure 6. End Suction Pump Modified with Air Extraction Capability.

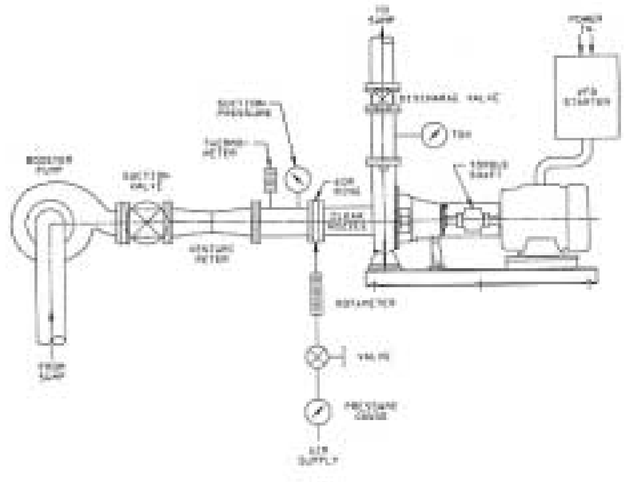

Figure 7. Air Test System.

ance degradation, but lack the ability to predict pump performance adequately over a broad range of pump geometries and applications. Therefore, an experimental test program was established with the intent of providing a range of data to be used as a basis for application guidelines and to investigate improved techniques for pumping liquids with entrained gas. Published literature describe many test programs involving the pumping of two-phase flow, most involve extensive investigation of one pump type and size. Schiavello [10] presents a comprehensive review and discussion of published test results/and analytical studies.

Scope of Test Program

The test program covered three different groups of pump configurations:

- End suction open impeller pumps
- End suction open impeller pumps with increased impeller to casing running clearances
- Special pump designs and considerations

Twelve different sizes of open impeller end suction centrifugal pumps with a specific speed range of 900 to 3000 were tested. Impeller diameters ranged from 14 in to 22.5 in, while test speed ranged from 880 rpm to 1780 rpm. The tests were performed using air as the entrained gas, with percentages by volume ranging from zero percent to 10 percent. Since many of the previously described applications are limited to five ft of positive suction head, most of the testing was performed as such. Some testing was performed with 15 ft of positive suction head, as a comparison against test results with five ft of positive suction head.

Test Method

All of the pump performance testing was performed on an open sump type facility as shown in Figure 7. A booster pump is used to supply the test system and a suction throttle valve is used to control the suction pressure of the test pump. A venturi is used to measure the flowrate of clear water flow upstream of air injection. An air injector as shown in Figure 8 was placed within three pipe diameters of the pump suction flange to provide an air-water mixture to the test pump. The air flow was measured using a rotameter with a pressure gauge to provide the proper volume of air. The percentage of air by volume is defined by the following:

$$\% \text{ Air} = \frac{\text{Air Volume}}{\text{Liquid Volume}} \quad (1)$$

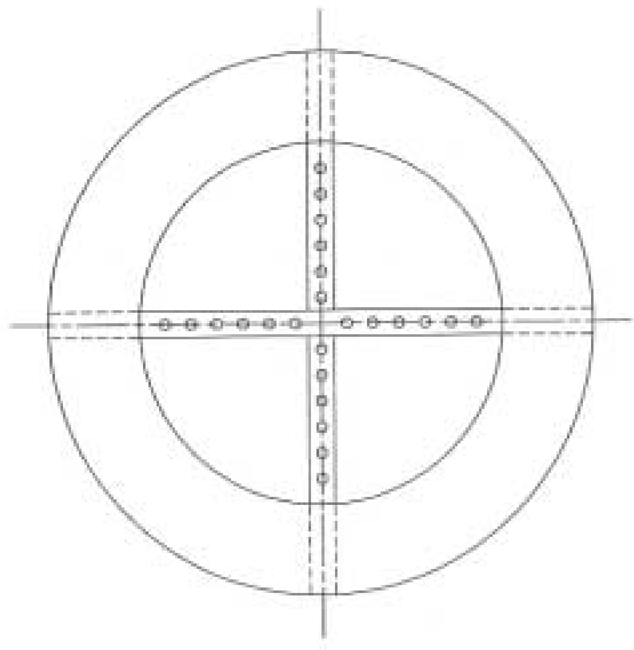

Figure 8. Injection Ring for Entraining Air in Suction Piping.

The percent air by volume is always referenced to the suction of the pump and is based on the suction pressure.

Details of the air supply calculation technique are included in the appendix.

For a portion of the testing, a section of transparent pipe was placed between the air injector and the pump. This was used to verify a homogeneous mixture of liquid and air was supplied to the pump. The transparent pipe (six in diameter) is shown in Figure 9 with six percent entrained air by volume, and with the pump operating near the best efficiency point at 1780 rpm. The same pump is shown in Figure 10, operating with six percent entrained air operating at 20 percent of the best efficiency point and 1780 rpm. Note the mixing action at low flow operation caused by impeller inlet recirculation and backflow. Pump performance was measured to Hydraulic Institute standards using pressure transducers, Bourdon tube gauges, calibrated motors and torque shafts depending on the pump size.

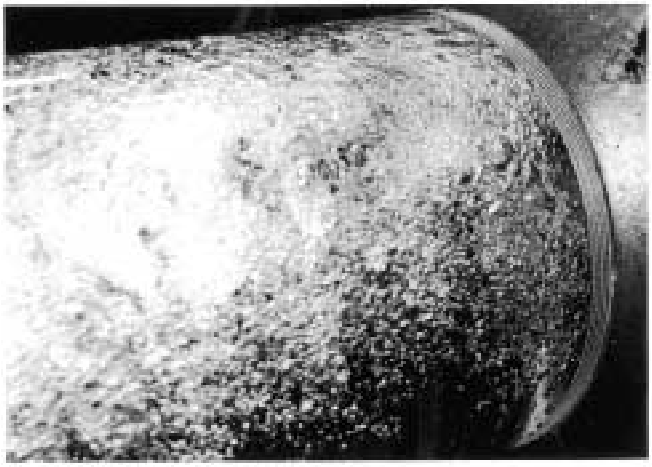

Figure 9. Transparent Suction Pipe with Six Percent Entrained Air by Volume, at Best Efficiency Point, 1780 RPM.

Figure 10. Transparent Suction Pipe with Six Percent Entrained Air by Volume, at 20 Percent of Best Efficiency Point, 1780 RPM.

TEST RESULTS

The data presentation format was driven by the need for an easy-to-use pump application guideline. All data was referenced to standard pump performance curves to allow quick calculation of performance with entrained gas. A correction factor to the pump head curve is defined as:

$$HF = \text{Head Correction Factor} = \frac{\text{Head Measured With Entrained Gas}}{\text{Head Measured Without Entrained Gas}} \quad (2)$$

Both values of head in (2) are taken at a common value of liquid flow.

A correction to the pump power curve is defined as:

$$PF = \text{Power Correction Factor} = \frac{\text{Power Measured With Entrained Gas}}{\text{Power Measured Without Entrained Gas}} \quad (3)$$

Both values of power in (3) are taken at a common value of liquid flow.

End Suction Open Impeller Pumps

Conventional open impeller pump designs are capable of reliably pumping liquids with less than five percent entrained gas. HF and PF curves are shown in Figure 11 for open impellers with normal running clearances (Figure 3), and a positive suction head of zero to five ft. The curves were developed from a compilation of test data taken starting in the late 1950s [11, 12].

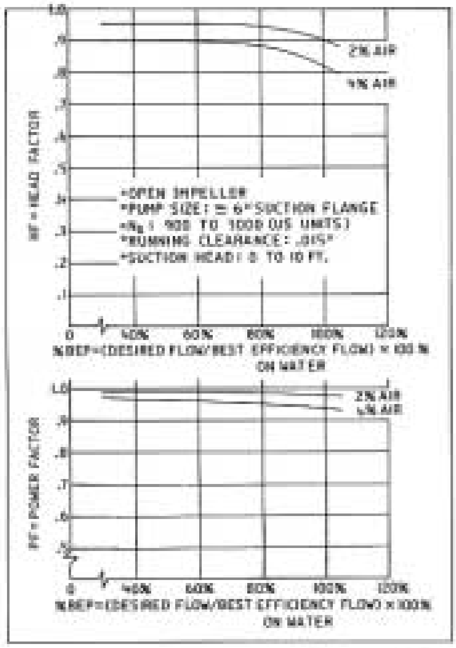

Figure 11. Head and Power Correction Factor vs Capacity, Zero Percent to Four Percent Air by Volume, Normal Running Clearance.

End Suction Open Impeller Pump with Increased Impeller to Casing Running Clearances

As discussed earlier, pumping liquids with five percent or greater amounts of entrained gas requires special consideration. As shown in Figure 3, one technique used to ensure reliable pumping is to increase the running clearance between the impeller and the stationary casing. HF and PF data shown in Figure 12 are taken from numerous pump tests with increased front clearance. All pump tests were run with either five percent or 10 percent air by volume, a positive five ft of suction head, and had a suction nozzle size of greater than eight in in diameter. The data presented in Figures 11 and 12 are for impellers with at least four vanes.

Special Designs and Considerations

Pumps with suction nozzles of less than or equal to eight in tend to be more susceptible to the detrimental effects of entrained air. The small passages at the impeller inlet are more easily choked by cavities of accumulated gas. Often changing to an impeller with less vanes will improve performance with large percentages of entrained gas. Impellers with two or three vanes (low solidity) have larger passages that are less susceptible to blockage by gas cavities. Impellers with fewer vanes also tend to have more turbulence at the impeller inlet. This helps to prevent accumulation of gas cavities. An end suction paper stock pump with a six in suction nozzle, three in discharge nozzle and 14 in impeller diameter was tested with 10 percent air at 1180 rpm. HF and PF are shown in Figure 13 for a five vane and a two vane impeller. The two vane impeller maintains a performance similar to larger pumps,

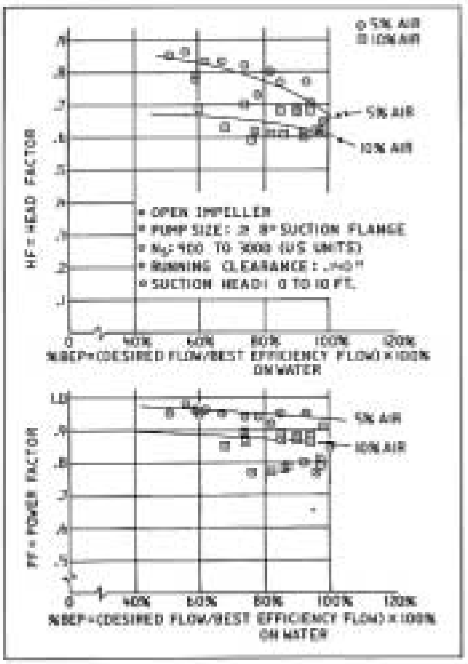

Figure 12. Head and Power Correction Factor vs Capacity, Five Percent to 10 Percent Air by Volume, Increased Running Clearance.

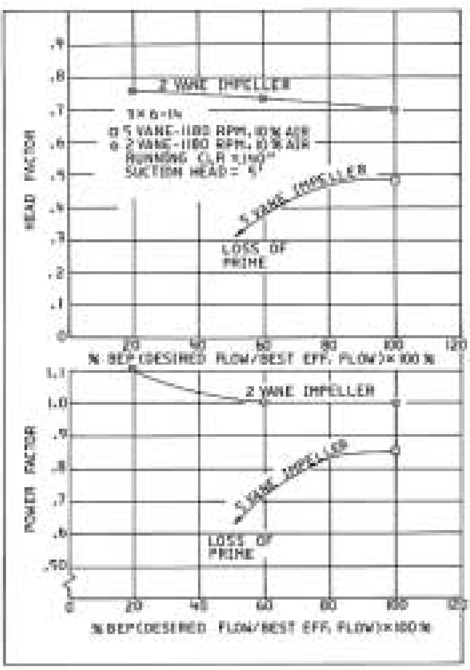

Figure 13. Head and Power Correction Factor vs Capacity, Effect of Vane Number.

while the five vane actually loses prime at capacities slightly less than the design condition.

As discussed earlier, increasing the suction head improves gas handling capability. The effect of increasing the suction head to 15 ft is shown in Figure 14. The five vane impeller loses prime with five ft of suction head, but pumps reliably with 15 ft of suction head.

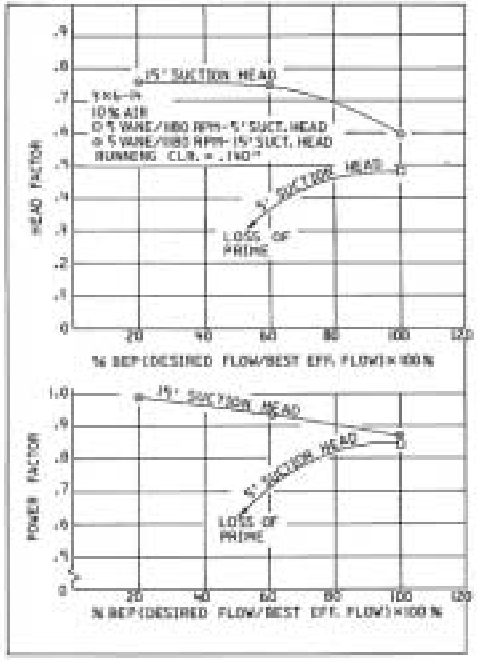

Figure 14. Head and Power Correction Factor vs Capacity, Effect of Suction Head.

The addition of an inducer to the inlet (Figure 4) can significantly improve performance when pumping entrained gases. As stated earlier, the inducer generates pressure, thus reducing the volume of gas entering the impeller. A three blade inducer, pumping water with six percent entrained air by volume at 75 percent of the pump design capacity, while operating at 1180 rpm, is shown in Figure 15. The same inducer and five vane impeller is shown in Figure 16 operating at 50 percent of best efficiency point (bep) with six percent entrained air. At lower suction velocities, the air tends to collect at the top of the suction pipe. As shown be seen in the photograph, the inducer acts to reentrain the air, greatly enhancing its pumpability and preventive loss of prime. The effect of adding an inducer to a five vane impeller is shown in Figure 17. The impeller loses prime with five ft of suction head without the inducer, but pumps reliably with the inducer and the same suction condition.

Figure 15. Inducer with Six Percent Entrained Air at 75 Percent of Best Efficiency Point, 1180 RPM.

Figure 16. Inducer with Six Percent Entrained Air at 50 Percent of Best Efficiency Point, 1180 RPM.

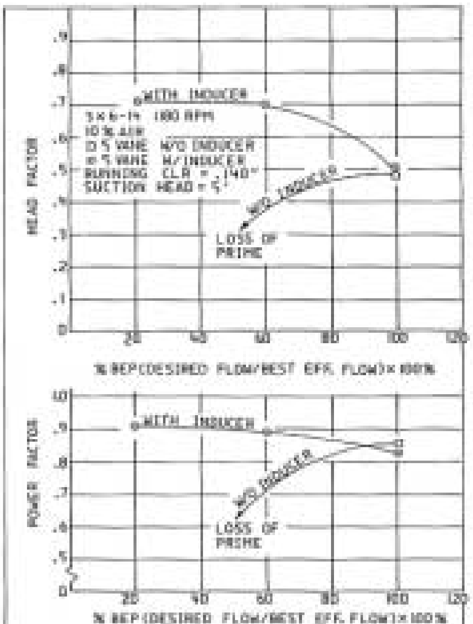

Figure 17. Head and Power Correction Factor vs Capacity, Effect of Inducer.

APPLICATION GUIDELINES

Application Information Requirements

To size a centrifugal pump properly for an air handling application, the following must be considered:

- Is it a new application or one for which a conclusive amount of gas can be said to be entrained in the pumped medium? or,
- Is it an existing installation that is not producing the required H-Q or that is losing prime either regularly or irregularly?

For the former, the information required besides the normal head and flow requirements are:

- The expected amount of gas expressed as a volume percentage of the liquid capacity at the pump suction, Equation (1).
- Complete suction system information including suction piping schematic representation and suction pressure relative to the impeller centerline. It must be emphasized that proper suction piping design rules are followed closely when designing a system in which any amount of air is to be introduced into the pumped medium. Eccentric reducers should always be used and the piping should slope up to the pump suction flange slightly, this helps to prevent air pockets from forming.
- Complete liquid characteristics including temperature and/or vapor pressure, percent fiber by weight if stock slurry, specific gravity.

The first two items allow use of the head and power correction charts (Figures 11 and 12), while the third informs the pump application engineer of any other special requirements that may be necessary for applying a pump to a given service.

For the latter, the amount of gas that is in the pumped medium is the unknown and must be estimated either through sampling, visual inspection through a transparent suction pipe, process calculations, or through examination of the installed pump. The following information about the installed pump can be used to estimate the amount of gas present in the pumped medium:

- Complete suction system details including piping schematic and suction pressure at the pump suction.
- TDH produced by the pump and power consumed. An estimate of the flowrate is also helpful.
- Complete details concerning the type of pump installed including model, size, rpm, impeller trim and running clearance.

Given this information and referring to Figure 11, or Figure 12, the amount of gas can be estimated and a modification can be made. If the pump is losing prime, the TDH and BHP should be measured immediately after repriming and restarting.

Pump Selection

Selecting a properly sized centrifugal pump for liquid and gas mixture depends primarily on the percentage of entrained gas or air. The application guidelines given here apply to open impeller centrifugal pumps with the following conditions:

- Pump rotational speeds of four to ten pole 50/60 Hz.
- Multivaned impellers (≥ four vanes).
- Approximately 5.0 ft positive suction head. Note: It is important that suction head be checked at the pump suction flange.
- Impeller trim diameter ≥ 85 percent of maximum impeller diameter.
- 50 percent bep ≤ 100 percent bep.
- Limited to pump with suction nozzles ≥ 8.0 in diameter (except vortex pumps).

The pump selection process can be divided into three parts for consideration:

- Conventional pumps (i.e., end suction, open impeller pumps with "normal" running clearances—0.015 in impeller to casing running clearance) with gas percentages less than five percent.
- Modified conventional pumps (i.e., those with increased running clearances—0.09 in to 0.180 in impeller to casing running clearance) with gas percentages from five percent to 10 percent.
- Specially designed pumps for gas percentages greater than 10 percent.

Conventional Pump (< Five Percent Entrained Gas)

Plots of HF and PF data are shown in Figure 11 as functions of percent bep flow for gas percentages of one percent through four percent. To use these charts, one makes an initial selection from a manufacturer's characteristics curves given desired TDH and capacity. A modifying head factor is then chosen, based on percent bep and percent gas from Figure 11, and divided into the desired head, yielding the developed pump head for the condition of zero percent entrained gas.

$$H_o = \frac{H}{HF} \quad (4)$$

where H = Desired TDH with entrained gas

H_o = Corrected TDH for 0% gas

HF = Head Correction Factor

The value H_o is then plotted for the desired flow on the pump characteristic curve and the impeller diameter can be chosen. The zero percent gas BHP is found from the characteristic curve and multiplied by the PF from Figure 11 for the percent bep and percent gas to yield the correct BHP for pumping with entrained gas.

$$BHP = (BHP_o)(PF) \quad (5)$$

where BHP = Horsepower with entrained gas %

BHP_o = Horsepower based on H_o and 0% gas

PF = Power Correction Factor

Example. Given a desired rating of 2500 gpm and 50 ft, five ft positive suction head and four percent entrained air, choose a pump, speed, impeller diameter, and BHP required.

- Using Figure 18 for characteristic curve with zero percent gas content at 880 rpm, find percent bep = 75.
- From Figure 11, HF = 0.89, therefore H_o = 50/0.89 = 56 ft.
- From Figure 18 impeller diameter = 15⅛ in × 17⅛ in and BHP_o = 47.
- From Figure 11, PF = 0.96, therefore, BHP = 0.96 × 47 = 45.

Note that for some ratings, it will be difficult to determine the correct percent of bep on the first iteration and a second iteration may be required. However, the HF and PF changes with percent bep are relatively small, so that the first iteration is usually adequate. Also, emphasis should be placed on applying the final diameter selection in a region of the characteristic curve between 50 percent and 100 percent of bep. Generated head can fall off sharply outside this region.

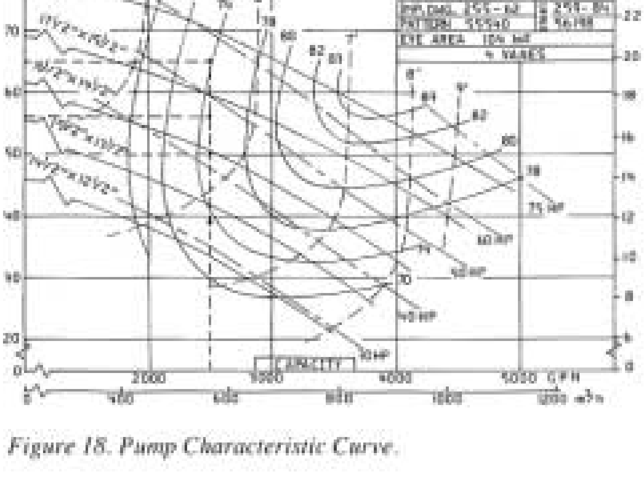

Figure 18. Pump Characteristic Curve.

Modified Conventional Pumps
(Five Percent to Ten Percent Entrained Gas)

Conventional pumps that have been modified for handling entrained gas will have an impeller to case clearance ranging typically from 0.090 in to 0.180 depending upon pump size. They are applied to gas percentage of from five percent to 10 percent by volume. The application guidelines are the same as those for the conventional pump, but the HF and PF are as shown in Figure 12.

Example. Given the same conditions as the previous example except six percent air, find the impeller diameter and required BHP.

- From Figure 18, percent bep = 75.
- From Figure 12, HF = 0.77, therefore H_o = 50/0.77 = 65 ft.
- From Figure 18, impeller diameter = 17 in.
- From Figure 12, PF = 0.93, therefore BHP = 0.93 × 55.5 = 51.5.

Specially Designed Pumps (Greater Than 10 percent Entrained Gas)

As discussed in the test results, small centrifugal pumps, those with suction nozzles smaller than eight in, exhibit higher head correction factors, when specified with two or three vane impellers. Therefore, when choosing pumps for gas entrained applications in this size range, a low solidity impeller is recommended. Figure 13 may be used to estimate head and power factors for 10 percent entrained gas.

Centrifugal pumps for handling entrained gas greater than 10 percent by volume at low suction pressures will sometimes be fitted with a gas extraction device, such as a liquid ring vacuum pump (Figure 6). They are sometimes applied to pumping high consistency fibrous suspensions and are highly modified to do so. Modifications include special stuffing box cover, specially designed impeller, repeller and inducers. They also require a mechanical seal to prevent entrained gas from entering through the stuffing box. The application of this type of pump involves properly sizing the liquid ring vacuum pump and controlling the level in the suction vessel, so that a constant suction head can be maintained. The amount of air to be removed depends upon the flowrate of pumped medium at the suction flange, the percentage of entrained gas, the process temperature, suction pressure, and vacuum pressure. Once the vacuum pump is sized, pump application becomes a matter of controlling these variables (particularly suction head and vacuum pressure). Since the gas is removed from the pumped fluid, selection of pump size can be performed without correcting for head and power losses.

Vortex or recessed impeller type pumps (see Figure 19) also can be used for applications above 10 percent entrained gas. They are lower in cost and complexity than a pump fitted with gas extraction, and can be used also when pumping large solids with the entrained air. Their efficiency is much lower, however, due to the large clearance and associated recirculation.

They are applied in the same manner as the modified centrifugal pump, but with different limitations. The HF and PF corrections for applying a vortex pump on 10 percent through 20 percent entrained gas [13] are shown in Figure 20. Just as when applying a modified centrifugal pump, these head and power correction factors are used with a vortex pump characteristic curve to determine impeller diameter and corrected brake horsepower.

The flow range limitation is from 40 percent to 120 percent of bep, but the pump is unstable with air contents of less than 10

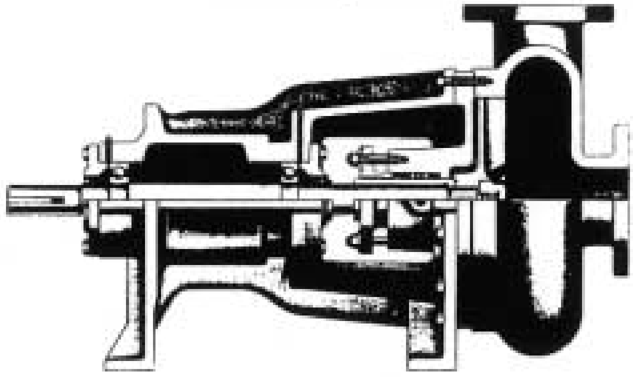

Figure 19. Vortex Pump.

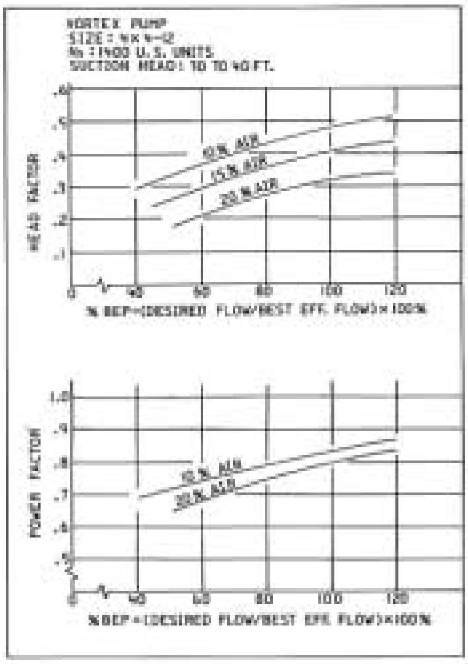

Figure 20. Vortex Pump Head and Power Correction Factor vs Capacity, 10 Percent to 20 Percent by Volume.

percent. The application of vortex pumps for less than 10 percent gas is therefore not recommended. Use of these head and power correction factors is also limited to a range of 30 to 40 ft of suction head. The authors wish to point out that caution should be exercised when using vortex pumps in air handling applications, since the guidelines shown in Figure 20 are based on a single pump test. This is an area that requires further investigation.

Factory Test Requirements

Since the application of gas handling centrifugal pumps of all types can be difficult, the authors have strived here to present data that is conservative. It is advisable for the buyer to request an installation list or evidence of other experience from the vendor. A factory test is advisable whenever applicable experience cannot be validated.

CONCLUSIONS

The effect of entrained gas on the performance of pumps can be readily tested in an industrial laboratory environment. A testing technique is described, which can be used to perform research or used for testing commercial pumps to verify performance before shipment to a user.

Data are presented showing the effect of up to 10 percent entrained gas on low to medium specific speed (900 to 3000 U.S. units) end suction open impeller pumps. The effect of up to five percent entrained gas on the head and power of conventional end suction open impeller pumps is relatively minor. Head and power correction factors are presented in easy to understand graphs. For five percent to 10 percent entrained gas, generally some type of modification to conventional pumps are required to ensure reliable operation and avoidance of losing prime. Increasing the running clearance between the impeller and casing is one such modification. Data is presented showing the effect of increased running clearance with five percent and 10 percent entrained gas.

All testing described above was performed with relatively low suction head of a positive five ft, since many of the applications described were limited to low suction heads. One set of data is presented showing the positive effects of increasing the suction head from five to 15 ft, with only five ft the pump lost prime at low flows, but pumped reliably with 15 ft of positive suction head. For small pumps (suction nozzle less than eight in in diameter), the small internal flow passages are more easily choked off by gas cavities, therefore reducing the number of impeller vanes can improve gas handling performance.

Results are shown for five vane and two vane impeller of the same size pump. The addition of an inducer to the pump suction reduces gas volume before it enters the impeller, thus improving gas handling performance. At low flows, the inducer helps to entrain gas into the liquid, preventing the formation of large gas bubbles in the impeller eye.

Special pump designs are required to pump mediums with greater than 10 percent entrained gas by volume. Vortex pumps are shown to pump up to 20 percent entrained gas by volume. Highly modified centrifugal pumps with gas separation and extraction are capable of pumping with up to 40 percent entrained gas by volume.

Application guidelines are presented that assist in the selection of proper pump configuration. The guidelines consider the percentage of gas by volume, pump size, operating point relative to the best efficiency point, impeller trim and suction head.

APPENDIX

Rotameters are generally calibrated for gas at a fixed supply pressure and are usually graduated in cfm, although some are graduated in percentage of a maximum flow in cfm. If air supply pressure is different from this calibrated pressure, the rotameter reading must be compensated. Likewise, the reading must be compensated for pump suction pressures different from atmospheric pressure.

Rotameter Reading =

$$\left[\frac{\text{Pcal.} + \text{Patm}}{\text{Ps} + \text{Patm}}\right] \left[\frac{34 + \text{Hs}}{34}\right] \left[\frac{\%\ \text{Air}}{100}\right] \left[\frac{\text{Q}}{7.48}\right] \tag{6}$$

Where:

Pcal	=	Calibration pressure of rotameter in psig.
Patm	=	Atmospheric pressure 14.7 psia.
Ps	=	Air supply pressure psig.
Hs	=	Pump suction head feet of H_2O.
34	=	Atmospheric pressure feet of H_2O.
% Air	=	Volume of entrained air in pumpage.

Q = Pumpage capacity GPM.

7.48 = Conversion factor gallons (U.S.) to cubic feet.

cfm = Cubic feet per minute.

REFERENCES

1. Doolin, J. H., "Centrifugal Pumps and Entrained-Air Problems," Chemical Engineering, p. 103 (January 1963).
2. Stepanoff, A. J., *Pumps and Blowers—Two Phase Flow*, New York, New York: John Wiley & Sons, Inc., pp. 262-264 (1965).
3. LeFur, B., David, J.F., Pecot, D., "The Influence of Occluded or Dissolved Air Contained in Water on Pump Cavitation," Proceedings of the IME, International Conference, Part Load Pumping Operation, pp. 97-104 (1988).
4. Mikielewicz, J., Wilson, D. G., Chan, T. and Goldfin, A. L., "A Method for Correlating the Characteristics of Centrifugal Pumps in Two-Phase Flow," ASME, Journal of Fluids Engineering, *100*, pp. 395-409 (December 1978).
5. Muench, R. A., "The Prediction of Pump Differential Pressure for Two-Phase/Two Component Compressible Flow," ASME Paper 76-WA/HT-75 (1976).
6. Turpin, J. L., Len, J. F., and Bearden, J. L., "Gas-Liquid Flow Through Centrifugal Pumps—Correlation of Data," *Proceedings of the Third International Pump Symposium*, Turbomachinery Laboratory, Department of Mechanical Engineering, Texas A&M University, College Station, Texas, pp. 13-20 (1986).
7. Murakami, M. and Minemura, K., "Effects of Entrained Air on the Performance of a Centrifugal Pump, 1st Report, Performance and Flow Conditions," JSME, *17*, (110), pp. 1047-1055 (1974).
8. Murakami, M. and Minemura, K., "Effects of Entrained Air on the Performance of a Centrifugal Pump, 2nd Report, Effects of Number of Blades," JSME, *17*, (112), pp. 1286-1295 (1974).
9. Murakami, M. and Minemura, K., "Effects of Running Clearance of Semi-Open Impeller Pumps Under Air Admitting Conditions," JSME, *19*, (136), pp. 1141-1148 (1976).
10. Schiavello, B.,"Two-Phase Flow Rotordynamic Pumps—Experiments and Design Criteria," Norwegian Society of Chartered Engineers, Course No. 7133, (1986).
11. Lubieniecki, V. M. and Roberts, R. N., "Test Report—Effect of Entrained Gas in Liquid Pumped on Pump Performance," Internal Report, Goulds Pumps, Inc. (1965).
12. Kalvelage, P.H.J., "Memoranda on Further Investigations of Air Handling in Paper Stock Pumps," Internal Report, Goulds Pumps, Inc. (1957).
13. Lubieniecki, V. M., "Test Report - Application of Vortex Pumps For Handling Liquids With Entrained Gases," Internal Report, Goulds Pumps, Inc. (1971).

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