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ALTERNATE METHOD FOR DETERMINING THE LIQUID PRESSURE RECOVERY FACTOR

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Abstract:

The standard method of determining the liquid pressure recovery factor, F_L, which is effectively the ratio of choked to non-choked flow for some condition, involves testing a valve in choked flow conditions to determine the value of the flow coefficient, C_{vc}, and comparing that value to the value of C_v in non-choked flow. The standard test procedure is difficult to follow with high-performance, pressure-regulating valves, which have capacities of flow and pressure far above many laboratories' capabilities. The author investigated an alternative method to obtain the term F_L and presents the findings in this technical report.

Laboratory testing was accomplished using a 2-inch standard pipe test bench with orifice plates, a butterfly valve, a globe valve, and a Venturi. Two tests were performed, the industry standard inline test and the new method of determining the value of C_v, free-discharge to simulate choked flow. The use of orifice plates, a Venturi meter and different valve designs were used to provide different levels of pressure loss, which impose different losses based on their geometry.

The values of F_L between the two methods had little variation, with the largest difference happening with the Venturi meter. Due to the Venturi's geometry, the pressure quickly recovered, which made the calculation and determination of C_v and F_L difficult for the standard and the hypothesized tests. The application of the hypothesized method appears to work well for devices which do not have built-in pressure recovery means (i.e. in the case of the Venturi meter a pressure recovery cone). The flow control devices which induce flow seperation had the best agreement between the values of F_L.

Keywords — **Hydraulics, Liquid Pressure Recovery Factor, Cavitation, Choked Flow, Minor Losses**

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I. INTRODUCTION

Accurate measurement of flow through conduits is a necessity for many applications. Several flow measurement technologies use a pressure differential to determine flow rates. Pressure differentials are commonly induced by Venturis, orifice plates, or Annubars but pressure differentials also happen across all types of valves. Valves are found in nearly every process and pipeline, with various pressure, chemical, and supply requirements.

The author aims to develop further understanding of how the pressure recovery factor, F_L is used and how the value is obtained for practical use in liquids. There is a similar term denoted pressure recovery factor which can be used on gases and other Newtonian fluids; however, only liquid flow was considered for this study. The valves considered in this study are a butterfly and a globe style valve. Three different sized orifices and a Venturi tube were also considered. The comparison of valves to orifices is not one to one, but the underlying principles of fluid mechanics can still be applied.

As the size of the valve or complexity of the valve increases, the system requirements need to increase to test a valve in a choked flow condition. The largest difficulty in determining F_L for valves is the increase in pressure required to choke larger and more complex valves. Many high-performance, pressure-regulating valves, for example, have flow and pressure capacities that are very difficult to test in a laboratory environment. Consequently, valve manufacturers are often tasked with estimating the choked performance of their valve. For this study the use of orifices and a Venturi demonstrate some other types of restrictions for comparison of the proposed method for the proposed approach for obtaining the value of F_L.

The intent of knowing F_L is to enable the determination of the maximum flowrate through a valve for a given upstream pressure. This can be useful in the event of a process line rupture to quantify the volume of liquid that may pass through a valve. The maximum liquid flowrate through a valve happens when the differential pressure reaches the terminal pressure drop, ΔP_T. The ΔP_T is the maximum possible pressure drop when considering the differential, where there is an upstream pressure, and the downstream pressure is the liquid's vapor pressure.

The current procedure from the American National Standards Institute/International Society of Automation, ANSI/ISA 75.02.01, dictates the value of F_L be found by testing at or below the vapor point of the liquid. The value of F_L is determined by comparing the values of the flow coefficient, C_V, non-choked to choked and can be used to calculate the flowrate in choked flow. The author proposes that F_L, or a value which closely approximates it, can be found by testing the valve in an atmospheric or free discharge scenario. The pressure recovery experienced by a free discharge is similar to that of the inline test where the ΔP_T has been reached because the maximum pressure differential across the valve is achieved and the pressure downstream has not recovered. This means that the flowrate cannot increase because the simulated choked flow condition; the greatest pressure differential experienced is the difference between the upstream pressure and atmospheric pressure.

A. Theoretical Background

As liquid flows through a valve, the pressure of the liquid decreases as the velocity increases as described by Bernoulli's principle. By using the pressure change across the valve along with a flow coefficient, the flowrate can be calculated. The flow coefficient C_v as shown in eq. 1, is useful as long as the pressure drop across the valve is less than ΔP_T, which can be calculated using eq. 2, which is from the Flow Control Manual by Kirman et al [5]. When the pressure drop across the valve is larger than ΔP_T, C_v and F_L are used to accurately adjust the calculated flowrate. Figure 1 demonstrates the expected flowrate vs pressure differential associated with a constant upstream pressure.

$$C_v = Q\sqrt{\frac{G_f}{\Delta P}} \quad (1)$$

Where Q is the flowrate in gallons per minute, gpm. ΔP is the pressure differential upstream to downstream in psi. G_f is the specific gravity of the liquid.

ΔP_T is defined as the downstream pressure reaches or goes below the vapor pressure of the liquid, at which point cavitation begins to form in the liquid. When the pressure drop across the valve is larger than ΔP_T, C_v and F_L are used to accurately adjust the calculated flowrate. Figure 1 demonstrates the expected flowrate vs pressure differential associated with a constant upstream pressure.

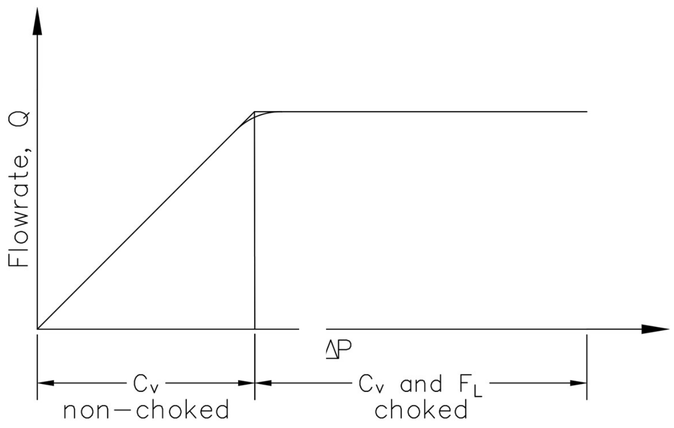

Fig. 1 A typical flowrate vs pressure differential chart showing the limits and usage of C_V. ΔP is the square root of pressure differential across the valve. The vertical line in between non-choked and choked flows denotes the terminal pressure drop, where flow is no longer affected by the pressure drop.

$$\Delta P_T = F_L^2\left(P_1 - \left(0.96 - 0.28\left(\frac{P_v}{P_c}\right)^{0.5}\right)P_v\right) \quad (2)$$

Where ΔP_T is the terminal pressure drop. P_1 is the upstream pressure in psia. P_v is the vapor pressure in psia. P_c is the thermodynamic critical pressure in psia.

When ΔP_T has been reached or passed, the term choked flow is typically applied. ANSI/ISA have defined choked flow as a 10% change in differential pressure with less than a 2% change in flowrate at a constant upstream pressure. The ANSI/ISA definition of choked flow is useful in determining which values of C_V are applicable to calculate the value of F_L as shown in equation 3. For the remainder of this paper the term non-choked flow will be used to describe any flowrate where the pressure difference is below ΔP_T. The use of ΔP_T is applicable only after the value of F_L has been determined for a given valve. Therefore, ΔP_T separates which values of pressure differences are associated with C_V and which are associated with F_L.

$$F_L = \frac{(C_v)_{choked}}{C_v} = \frac{Q_{max}}{C_v\sqrt{\frac{P_1 - F_F P_v}{G_f}}} \quad (3)$$

Where $(C_v)_{choked}$ is the value of C_v in choked flow. Q_{max} is the maximum flowrate in gpm for a set upstream pressure. F_F is 0.96 in most cases or can be calculated as $0.96 - 0.28\sqrt{\frac{P_v}{P_c}}$.

Atmospheric or free discharge displays a similar type of pressure drop to ΔP_T where there can be no change in flow produced by adjusting downstream pressure. In the case of the inline test, once choked flow is reached, the flowrate through the system is not impacted by further opening the downstream control valve. In the case of atmospheric discharge, the flowrate is dictated by the upstream pressure alone.

II. LITERATURE REVIEW

Baumann [2] introduced the C_f, critical flow factor, later renamed liquid pressure recovery factor, F_L, with guidance on how C_f applies in flow control and valve sizing equations. Baumann stated that C_f can be used to modify C_v to increase accuracy under cavitating flow schemes. C_v over predicts the flow through a valve as the pressure differential increases to the critical pressure difference as called by Baumann, which is when the downstream pressure reaches vapor pressure.

Rahmeyer [6] looked at the F_L of 2 – 36-inch, geometrically similar valves and determined F_L of the different valve types independent of size. The data was collected for globe valves, gate valves, ball valves, and butterfly valves. Before this study of pressure recovery, the primary research was done on 2-inch to 4-inch diameter valves, by looking at a wide range of valve sizes Rahmeyer established curves of F_L vs C_v/d^2 independent of the size of the valve.

Tullis [8] described the difference between choking and supercavitation of valves. Through testing done at Colorado State University, Tullis used sigma, σ, or the cavitation index, to quantify the level of cavitation happening downstream of a valve. The specific scope of Tullis' work looked at how σ can be used to predict supercavitation in a system. Supercavitation is extremely unstable and causes erosion downstream of the valve, compared to erosion caused by cavitation which happens close to the valve. Tullis also described how the discharge coefficient, C_d , responds to choked or supercavitiating flow. Rather than using F_L Tullis used both C_d and σ to predict the flow through a choked valve.

The ANSI/ISA 75.02.01-2008 [4] Control Valve Capacity Test Procedures describes the standard for testing and obtaining values of F_L . This test procedure guide is the industry standard for calibrating and determining the values of C_v and F_L as well as many other terms which are not relevant to this paper.

Ball et al. [1] developed trends of butterfly valve behavior based on the geometry of the disc, and size of the valve. The use of σ was predominantly used, however the analysis of losses across the valve led to a trend of values of C_d.

Tullis [9] discussed the effects of choking a valve and states that during "choking the valve operates as if it were free-discharging (but into a vacuum)". When the valve is choking or free-discharging, the effectiveness of terms like C_v and the discharge coefficient C_d decrease. As the C_v and C_d, change they begin to overpredict the flowrate through the valve.

Kirman et al. [5] discussed the typical formation and behavior of pressure recovery across a valve. With a constant upstream pressure, the flow rate will increase linearly with increasing pressure differentials until cavitation begins to limit the flow. Part of the reason cavitation restricts the flow is due to air bubbles, which fall out of solution and act as a blockage to flow.

B. Summary of Findings

The uses of F_L are predominately associated with calibration and flow measurement. While it is commonly advised to size a valve or meter so that it operates in normal flow, the use of F_L gives a better representation of the flow rate through a valve in choked flow.

Since the original formation of the term C_f or F_L, there has been no change in the basic testing procedure. There has been little or no research on the topic of a free discharge to determine F_L . The estimation by Tullis [9] of comparing choked flow to free discharge has yet to be fully investigated.

In this study, the application of a simulated F_L will be used to describe the flow characteristics of an atmospheric discharge to better understand the capacities of this procedure compared to the ANSI/ISA standard. The comparison will provide insights on how the ANSI/ISA standard could be adapted to include an alternate method of determining F_L . This procedure will be able to determine the performance of valves which previously could not be tested for F_L in a laboratory setting.

III. METHODOLOGY

The data for this study was collected at the Utah Water Research Laboratory (UWRL). The pressures for the inline test were measured at the locations described by ANSI/ISA of 2 pipe diameters, D, upstream and 6D downstream of the device being tested as determined by Sanders [7]. The pressures for the atmospheric or free discharge were taken 2D upstream and referenced against atmospheric pressure.

The test bench was supplied by a pump to a 6-inch supply line, the line was reduced to a 2-inch diameter, schedule 40 steel pipe with the above-mentioned pressure taps. The upstream pressure was regulated by a 4-inch globe valve, and the downstream pressure was regulated by a 6-inch butterfly valve as shown in Figure 4.

For the free discharge test, the upstream section of piping remained the same as the inline test. The downstream section of piping was removed, and a catchment was used to direct water back into the waste channel.

The devices tested are shown in Figure 2 and listed as follows:

2-inch Orifice Plates (beta ratios of 0.3, 0.5, and 0.7)
2-inch Venturi Meter
2-inch Butterfly Valve
2-inch Globe Valve

C. Inline Test

The inline test was conducted in the manner prescribed by ANSI/ISA 75.02.01. The initial setup of the system is unique for each laboratory, so the procedure used is described hereafter. The unit under test was installed in the test bench; a pressure transducer was connected to the pipeline with tubing at the upstream and downstream tap locations as shown in Figure 3. The pressure transducer and reference meter were time averaged to obtain measured values.

Fig. 2 Image of the valves and meters being tested. Upper: 0.3, 0.5, and 0.7 β ratio orifice plates. Left: butterfly valve. Right middle: globe valve. Lower right: Venturi. All valves and meters are for 2-inch diameter pipelines

The test bench was filled with water, and the air was removed from the system. The tubing which connects the transducer was allowed to flush the air out to ensure proper readings of the transducer. The test bench was then isolated from the pump, and the transducer was spanned to the appropriate pressure ranges and a zero for gauge pressure was established.

The test procedure described in ANSI/ISA 75.02.01 is to maintain a constant upstream pressure, and check the largest possible pressure differential to ensure choked flow. The pressure differential is then adjusted to various flowrates to determine the flowrate versus pressure differential curve for the unit under test. Each flowrate and accompanying pressure difference were recorded.

Fig. 3 Image of the test setup with an orifice plate installed; flow is left to right. The pressure taps were connected via plastic tubing to the pressure transducers, where one measured the pressure upstream and one measured the pressure downstream.

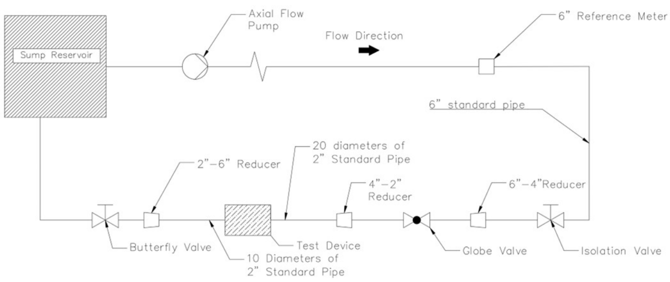

Fig. 4 Diagram of the inline test setup.

D. Atmospheric Discharge Test

The atmospheric-discharge test is not described by ANSI/ISO 75.02.01 or AWWA Quarter Turn Valves. The setup and procedure was similar to the inline test where a device was installed to the upstream pipe section. However, the downstream piping was removed, as shown in Figures 5 and 6. For the butterfly valve and orifice plates required bolting an open-bore flange on to the downstream face to secure the flow control device to the piping. The pressure transducer was then connected to the upstream pressure tap and was open to atmospheric pressure on the other port.

The pipeline was flushed of air as was the tube connecting the transducer. The transducer and reference meter were again time-averaged. The transducer was spanned for the proper pressure range and the zero for gauge pressure was checked and reset if necessary. The pressure differential and flowrate were recorded and the test procedure repeated for a different flowrate.

Fig. 5 Image of the atmospheric discharge test configuration with an orifice installed; flow was right to left. The catchment pipe on the left is set a distance away from the test device as to not draw a vacuum on the downstream end of the orifice. The pressure was monitored from the upstream pressure tap.

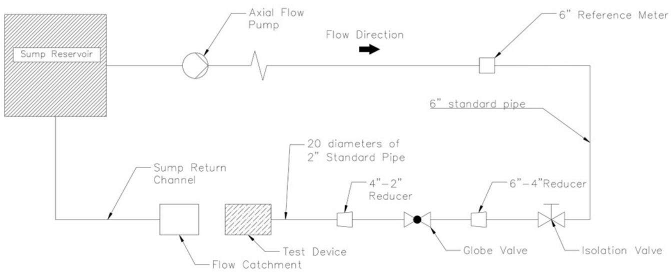

Fig. 6 Diagram of the atmospheric discharge test setup

E. Data Processing

After the initial pressures and flowrates were collected the values of C_v and F_L were calculated across each data set from each test. The data was separated into the ranges of applicability as defined by ANSI/ISA where data that showed a 10% change in pressure with less than a 2% change in flowrate were categorized as choked flow and used to determine values of F_L by using equation 3. The values of non-choked flow were used to determine the value of C_v by using equation 1.

The values of F_L were compared by their percent difference, as calculated by equation 4.

$$Percent\ Difference = \frac{F_L^* - F_L}{F_L} * 100\% \quad (4)$$

Where F_L^* is the atmospheric discharge value. F_L is the ANSI/ISA standard for determining the value of F_L.

One of the other metrics for determining valve and meter efficiency is the dimensionless loss term K. The values of K were calculated for each device using Equation 5 and then compared to the device's value of F_L.

$$K = \frac{2g\, h_l A^2}{Q^2} \quad (5)$$

Where g is gravitational acceleration, h_l is head loss across the valve, A is flow area of the pipe in and Q is flowrate. All terms need to have consistent units to ensure non-dimensionality for K.

IV. RESULTS AND DISCUSSION

This section contains the findings from the laboratory testing accomplished at the UWRL and presents the calculated values of F_L for the devices tested. The data of interest is presented as values of F_L, which will be compared between the inline and atmospheric discharge. The percent difference in the results will be used to show the variability of the results relative to the inline test approach.

The definition from ANSI/ISA was used to define which flow is choked, the values of F_L were calculated using equation 2. The values of F_L for the atmospheric discharge were calculated by comparing the value of C_v of atmospheric discharge and the C_v associated with non-choked flow inline. The values of F_L where averaged for each device in each test scenario as shown in Figure 7 and Table 1.

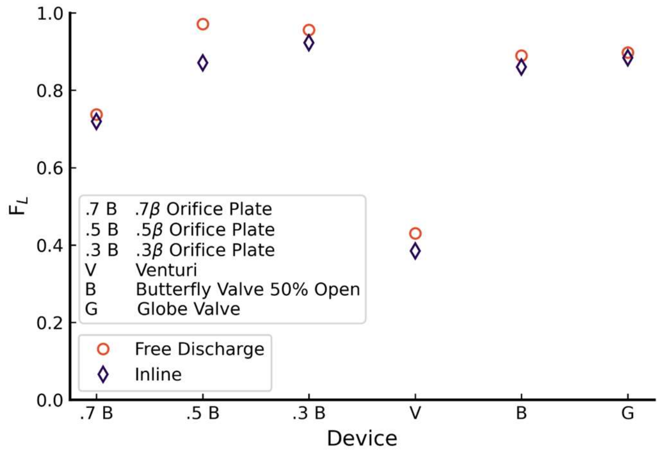

Fig 7 Calculated values of F_L for each valve and meter for the inline and atmospheric discharges

Two of the flow control devices had larger errors compared to the other devices. The percent error of F_L for the Venturi behaved abnormally compared to the other valves and meters tested. This is likely due to how and where flow is controlled through the Venturi. As flow approached the converging cone the flow behaved similarly to flow through a nozzle and as the flow passed through the throat there could have been an inconsistent point of flow control. Once the flow entered the recovery cone there was flow separation on part of the cone while the flow remained attached on other sections of the Venturi. This behavior was observed in free discharge, and may have happened during the inline test as well causing inconsistent values of C_v.

In addition, the values of the 0.5 β orifice plate also seemed to misbehave compared to the rest of the tested devices. The test was rerun to determine if there was an error in procedure, from the second test the values of F_L were shown to be highly repeatable.

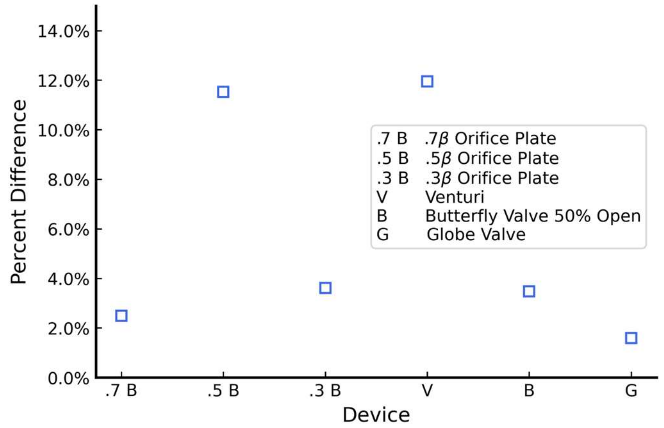

Fig 8 The percent difference between the values of F_L from ANSI/ISA standard compared to the atmospheric discharge.

Table 1 – The calculated values of F_L for inline and atmospheric tests with the calculated percent differences.

Device Type (Opening)	F_L (inline)	F_L (atm)*	Percent Error
0.7 β	0.719	0.737	2.5%
0.5 β	0.871	0.971	11.5%
0.3 β	0.923	0.956	3.6%
Venturi	0.384	0.430	11.9%
Butterfly (50% open)	0.860	0.89	3.5%
Globe Valve (100% open)	0.884	0.898	1.6%

*$F_L(atm)$ are values associated with the atmospheric discharge

Depending on the style of the valve or meter the free discharge typically over predicted the value of F_L. From each value of F_L, the values were used to calculate the theoretical flowrate as shown in Figure 9. For each data set presented the theoretical flowrates which most closely aligned with the actual flows recorded. The 0.7 β ratio orifice and the butterfly valve most closely matched the actual flowrates. On average, the flowrates associated with the theoretical values either over or under predict the actual flowrate up to 12%.

The difference in performance between the two procedures is shown in Figure 9 where ΔP_T is shown as calculated from F_L inline and free-discharge. Due to the difference in F_L between the two procedures, ΔP_T calculated from free-discharge was at a larger pressure differential comparted to ΔP_T calculated from the inline test. This difference in F_L had impacts on calculating the flowrate through the system. The difference shows some of the limitations associated with the proposed procedure were the difference in F_L changes when the maximum flowrate is achieved.

The difference in performance of the two procedures is also highlighted by the over prediction of the maximum flowrate. For each of the tested devices the theoretical flowrate calculated from the free discharge is larger than the theoretical flowrate from the inline test.

Figure 10 shows the comparison of F_L to K, with a collection of previously recorded data supplied by the UWRL. The trend presented by the UWRL data shows the larger the loss through a flow control device, the closer F_L gets to one. The data collected for this project follows that trend for both the inline and free discharge procedures. The trend of all the data shows there is a positive correlation between F_L and K.

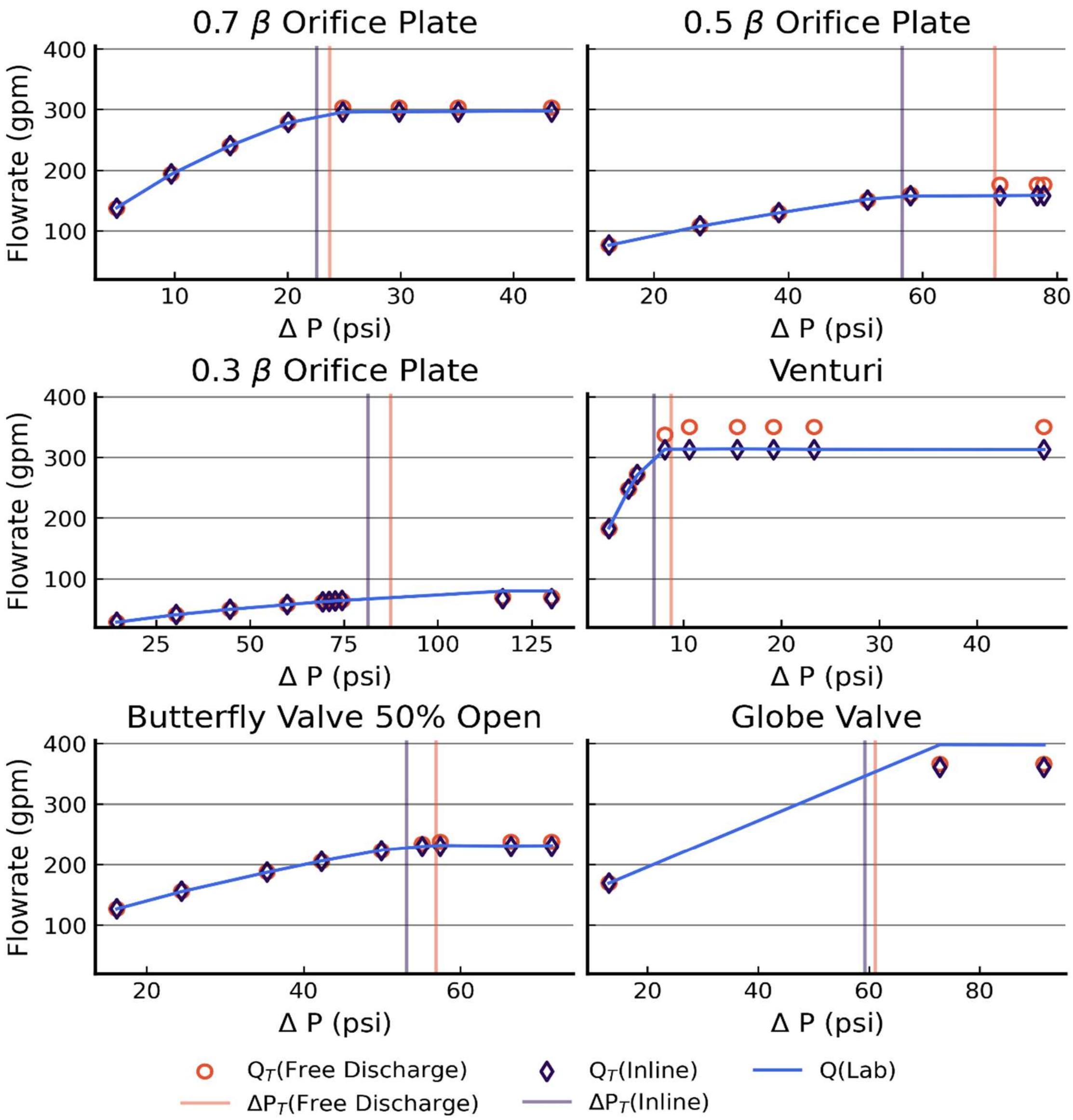

Fig 2 The flowrate as recorded by the reference meter, $Q(lab)$, the calculated flowrate from the ANSI/ISA standard, $Q_T(Inline)$, and the calculated flowrate from the atmospheric discharge, $Q_T(Free\ Discharge)$

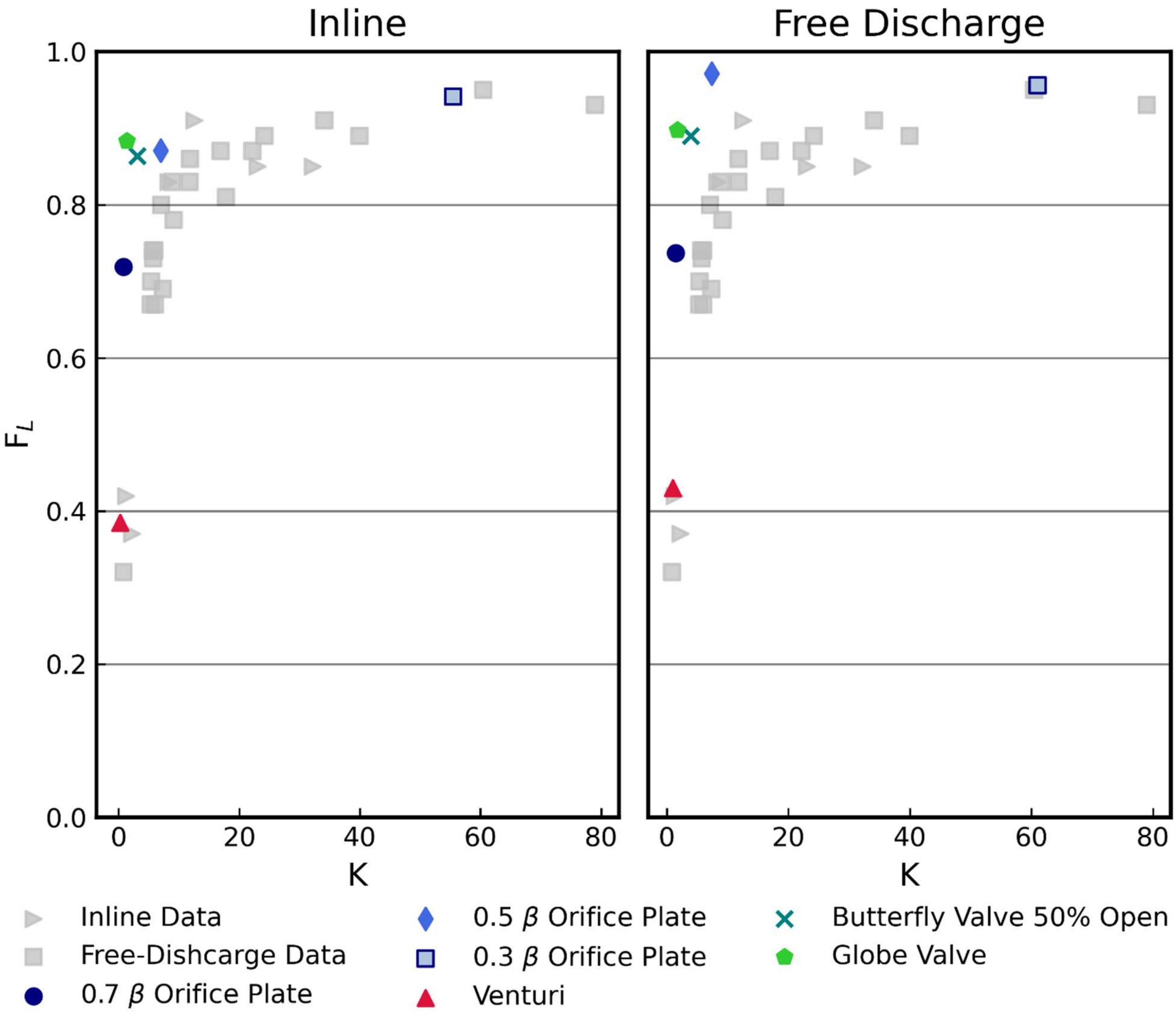

Fig 10 A comparison of minor losses, K, and liquid Pressure recovery factor, F_L. In grey, data collected at the Utah Water Research Laboratory where values of K and F_L were calculated for different calibrations both inline and with atmospheric discharges

V. CONCLUSIONS

This report demonstrates the process of determining the value of F_L through an atmospheric discharge across multiple valves and flow meters through laboratory testing. The motivation of the research comes from the difficult nature of obtaining F_L of certain valves using the standard procedure. Depending on the valve type, trim, and available pressure the value of F_L may be undefinable in a laboratory inline test due to the available pressures and flows at a given testing facility. The question became is there a comparable way of determining F_L through other means.

The research conducted by the author at the UWRL examined the standard test procedure as determined by ANSI/ISA, testing multiple flow control devices in choked flows, and decreasing the pressure differential to determine the multiple values of C_V across the choked and non-choked flows. The author tested multiple flow control devices in an atmospheric discharge to compare the respective values of F_L.

The use and development of the term F_L was primarily accomplished by Baumann [2], [3]. To add to Baumann's work, the author proposes that when the value of F_L cannot be determined by the ANSI/ISA procedure, the process of using an atmospheric discharge to calibrate for the F_L could be used with reasonable accuracy. The data as presented in Figure 8 and Table 1 demonstrate for most of the valves and the meters, the difference between the inline and atmospheric values of F_L may be less than a 5% difference.

The use of F_L is not common due to most valves and meters being used in systems where the flowrate is kept in the non-choked flow range. However, the applicability of F_L in choked flow conditions or inline break situations demonstrates the need for the term. Depending on the style and trim of the valve being tested the values of F_L can be difficult to obtain. However, through an atmospheric discharge test a reasonable approximation of F_L can be found.

The small percent errors of the test scenarios demonstrated the usefulness of this technique. The values of F_L obtained through atmospheric discharge represent a more accurate value of flowrate than can be found by C_V alone, which happens when the value of F_L cannot be determined. The atmospheric discharge would require a less powerful test system than an inline test would require.

F. Recommendations for Practice

Use the ANSI/ISA standard procedure for determining the value of F_L, as this value will be the most accurate for determining the value of choked flowrates.

If the test facilities are insufficient to obtain the value of F_L use an atmospheric or free discharge test to approximate the value of F_L . The author recommends, when calculating flowrates, to add a 5-10% buffer range due to the variability in the results.

G. Future Work

The testing of more types of valves, especially valves with cavitation resistant trims, as these types of valves can be difficult to produce similar effects as seen in this study.

The testing of geometrically similar valves with varying sizes as the tests conducted by Rahmeyer [6] could be redone but using atmospheric discharge and the results could be compared.

In conclusion, using a free or atmospheric discharge to determine an approximate value of F_L yields similar all be it slightly higher value than the ISA standard. The procedure described in this paper is not meant to replace the ANSI/ISA procedure but is to allow for a representative value to be found through facilities with less capability than would be required to accomplish the inline test.

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