A NEW APPROACH TO DESCRIBE THE GAS THROUGHPUT CAPACITY OF GAS LIFT VALVES

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ABSTRACT

Gas passage performance of gas lift valves under dynamic conditions has only been studied in the last twenty years. Proper assessment of gas injection rates at valve operating conditions requires the use of sophisticated measuring and control equipment only a few companies possess; and involves tedious and time-consuming data acquisition procedures. As a result, even today many gas lift installations are designed without properly accounting for the dynamic behavior of the operating gas lift valve.

The authors applied a novel approach to the description of gas lift valve performance and used Computational Fluid Dynamics (CFD) techniques to determine the valve's gas passage characteristics. CFD calculations provide a numerical solution of the governing equations (the conservation of mass, energy, etc.) that can be written for a flowing fluid. To facilitate the simultaneous solution of the governing equations the flow space (the inside of the valve available for gas flow) must be divided into sufficiently small final volumes i.e. cells. Since the accuracy of flow modeling greatly depends on the proper setup of these cells the paper fully describes the spatial distribution to be utilized.

After the cell structure of the gas lift valve's inside gas passage path is properly set up, CFD calculations allow the determination of gas volumes passed by the valve under static conditions for different combinations of valve stem travels, injection, and production pressures. In dynamic conditions, however, valve stem travel is a function of the net opening force developing on the tip of the valve stem. Since this force can be found by integrating the pressure distribution on the valve stem tip, an iterative procedure was developed to describe the valve behavior. The final result of the proposed model is the dynamic performance curve of the gas lift valve i.e. the injected gas rate vs. injection, production, and dome charge pressures. The procedure developed by the authors gives gas injections rates very close to those received from the universally-applied **RP 11V2** model.

INTRODUCTION

Although gas passage characteristics of gas lift valves are of paramount importance in gas lift technology, the industry did not investigate the problem in depth for many years. In the past, the performance of gas lift valves was described by static force balance equations and on the assumption that valves while open behave like a square-edged orifices. The valve was assumed to quickly and fully open as soon as the injection and production pressures satisfied the opening conditions. When fully open, the gas flow rate through the valve was computed based on the valve's port size and the equation originally proposed by the **Thornhill-Craver Co.,** valid for flow of ideal gases through fixed orifices. Gas lift valves, however, do not provide a constant flow area because the valve stem rarely lifts completely off the seat. The position of the stem, in relation to the valve seat is a function of the pressure conditions; therefore the valve acts as a variable orifice.

In one of the first papers [1] investigating this problem the authors state that the gas lift valve tested (a CAMCO R-20) behaved as a variable-orifice Venturi device and not as a simple orifice. A Venturi device is a converging-diverging nozzle in which the minimum flowing pressure occurs at its throat and there is a considerable pressure recovery downstream of the throat. The cross sectional area of the throat changes with the position of the valve stem which, in turn, varies with changes in the injection and/or production pressures. In conclusion, the pressure acting on the tip of the valve stem never equals injection pressure, as suggested from the static force balance equations.

The first practical investigation on the dynamic performance of gas charged bellows valves was done by **L. A. Decker** [2] who laid the foundation for present-day valve testing procedures. He derived the formulae to describe the behavior of the bellows assembly and introduced the concept of the bellows load rate. His analytical model allows the determination of the valve stem position as a function of the mean effective pressure acting on the bellows area.

It was the spring-loaded valve without bellows charge which was first experimentally investigated for its gas passage behavior. In normal operation this valve never opens fully and the pressure upstream of the port is very close to production pressure both in the open and in the closed positions. The original manufacturer, **MERLA Tool Corp.**, realized the need for flow capacity data on such "throttling" valves and performed hundreds of flow tests started in the early 60s [3, 4] and made the results available to the gas lift industry.

Research into the dynamic behavior of gas lift valves received a new impetus in the late 1980s after the founding of **TUALP** (Tulsa University Artificial Lift Projects), an industry-sponsored research consortium. Several papers [5 – 8] were published covering the main results of many years' experimental work. It was understood that gas passage through gas lift valves can occur under two different flow patterns: orifice and throttling flow. Orifice flow is very similar to gas flow through a fixed choke, whereas throttling flow resembles flow through a variable area **Venturi** device. The **orifice flow** model occurs with the valve stem at its maximum travel when the valve port behaves as a fixed orifice. For a constant injection pressure decreasing production pressures entail an increase of the gas rate until critical conditions are reached; upon further decrease in production pressure the injection rate remains at its critical value. In **throttling flow** if production pressure decreases below the injection pressure the gas rate increases due to the increasing pressure differential across the valve seat. After reaching a maximum value, injection rate linearly decreases with production pressure until gas flow ceases at the closing production pressure.

Mainly based on the systematic work performed at **TUALP** the first edition of the API publication "Gas-Lift Valve Performance Testing" (**API RP 11V2**) [9] came out in 1995. It covers recommendations on the proper measurement and testing procedures for gas lift valves and also contains a calculation model for determining of gas throughput capacities of valves. A closely related procedure is used by the Valve Performance Clearinghouse (**VPC**) a joint industry project founded in 1996 to provide experimental performance data on gas lift valves for the industry.

APPLICATION OF CFD METHODS TO DESCRIBE GAS FLOW THROUGH GAS LIFT VALVES

Basic Flow Equations

Gas flow inside of a gas lift valve is characterized by the Navier-Stokes equation representing Newton's second axiom and can be written in the following form:

$$\frac{\partial \vec{v}}{\partial t} + \mathrm{div}\left(\vec{v} \circ \vec{v}\right) = \vec{g} - \frac{1}{\rho}\mathrm{grad}\, p + \vec{v}\,\Delta\vec{v} + \frac{\mu+\zeta}{\rho}\mathrm{grad}\,\mathrm{div}\,\vec{v} \qquad \mathbf{1}$$

The conservation of mass is described by the continuity equation:

$$\frac{\partial p}{\partial t} + \mathrm{div}\left(\rho\,\vec{v}\right) = 0 \qquad \mathbf{2}$$

Conservation of the energy of the flowing fluid is expressed by the following equation:

$$\frac{\partial}{\partial t}\left(\frac{v^2}{2} + h\right)\rho + \mathrm{div}\left[\left(\frac{v^2}{2} + h\right)\rho\vec{v} - \lambda\nabla T\right] = \frac{\partial p}{\partial t} \qquad \mathbf{3}$$

The three basic differential equations governing the flow conditions have five unknowns this is why two more equations are needed for an unambiguous solution. These are provided by (a) the equation of state for the flowing fluid, and (b) the equation describing the change of the enthalpy with the state parameters, as given in the following:

$$\rho = \rho\left(p, T\right) \qquad \mathbf{4}$$

$$h = h\left(p, T\right) \qquad \mathbf{5}$$

The five equations defined previously constitute a system of equations with altogether five unknowns; making the simultaneous solution of them theoretically possible.

Numerical Solution of the Flow Equations

Analytical solution of the basic flow equations **1** – **5** is possible only for very simple cases so numerical solutions, so called finite element models are usually applied. The Computational Fluid Dynamics (CFD) program package used in this paper performs a numerical solution of the governing equations using finite volumes. This are constructed by dividing the flow space into a finite number of cells having finite volumes and connected to each other. Calculations are made at the geometrical centers of the cells (the node points) where fluid and flow parameters are calculated first. Finally the algebraic equations resulting from the integration of the basic differential equations at cell boundaries are solved to get the five unknowns at node points.

The Geometrical Model of the Flow Space

Results of Computational Fluid Dynamics (CFD) calculations heavily depend on the proper setup of the geometrical model of the flow space because improper models can cause convergence difficulties and erroneous results. In our case the geometrical model means the representation of the internal space of the gas lift valve where gas flow takes place. The part of the valve to be investigated is shown in **Fig. 1** where the space available for gas flow constitutes the flow space for the CFD calculations. This space must be filled up with interconnected hexahedrons representing the cells. For ensuring higher accuracies and faster solutions the hexahedrons must be chosen so that they are as close to cubes as possible.

The most important part of the flow space is around the valve stem tip for two reasons: (1) here is the most complicated geometry involving the valve ball that is difficult to approximate with hexahedrons, and (2) proper knowledge of pressure distribution on the valve stem tip is essential to calculate the forces acting on the valve stem. **Fig. 2** displays the details of the cell structure applied at this critical part of the flow space.

The remaining parts of the flow space are shaped (a) as a tube (below the valve port), and (b) as an annulus (above the valve port). These are much easier to represent than the region around the valve stem tip. Finally, the total flow space of the gas lift valve is approximated as shown in **Fig. 3**.

Using the cell structure given in **Fig. 3** involved a total number of cells reaching to 75,000. Since CFD program run time was excessive with such huge numbers of cells the possibility of simplifying the flow geometry was investigated. In order to reduce the number of cells while sustaining calculation accuracy two simplifying modifications were tried as given in the following:

1. Replacing the four gas inlet ports by one of the same total cross-sectional area, and
2. Trimming the two ends of the flow space by decreasing the length of:
    a. the tube-like shape downstream of the valve port, and
    b. the annulus upstream of the valve port.

The result of these modifications was the reduction of the required cells' total number from the original to around 10,000 cells; the final cell structure is displayed in **Fig. 4**. Computational time when using the new flow space configuration has drastically dropped to about one tenth of the original run times.

To ensure that calculation accuracy was not sacrificed by the reduced number of cells, a set of control calculations was performed. Comparisons of the final results of pressure distributions along the flow path showed negligible differences so the use of the simplified flow space configuration was justified.

Simulation Results

The theoretical and practical considerations detailed so far were applied to the determination of the gas throughput capacity of a 1 in. OD, CAMCO BK-1 type gas lift valve with a 3/16 in. port.

Simulations of gas lift valve behavior consisted of the following main tasks:

1. First, a valve stem travel (measured from the valve's closed position) was assumed.
2. Using carefully measured dimensions of the disassembled valve the flow space was constructed.
3. Next, values for the prevailing bellows charge, injection, and production pressures were assumed.
4. By running the CFD program the governing equations **1** – **5** were solved and the spatial distributions of pressure, velocity, and temperature were calculated.

CFD calculation results allowed the determination of the following important operational parameters of the gas lift valve under the assumed conditions:

1. The net vertical force acting on the well stem.
2. The gas flow rate across the gas lift valve.

Fig. 4 shows the pressure distribution inside the valve for an example case.

CONSTRUCTION OF VALVE PERFORMANCE CURVES

The Valve Performance Curve describes the dynamic performance of the gas lift valve and presents the valve's gas throughput capacity for different injection and production pressures at a given bellows charge pressure. As proved by many investigators, gas lift valves can have two main kinds of behavior: orifice flow or throttling flow models. Orifice flow occurs when valve stem travel is at its maximum and the valve behaves like a simple orifice. Throttling flow, on the other hand, occurs at smaller stem travels when the valve behaves as a variable-orifice Venturi device with a restricted gas injection capacity.

It follows from the nature of the two possible flow conditions that orifice flow is easily simulated by the CFD calculations previously described. This is due to the fact that the valve stem is always at its maximum upward position so gas rates can easily be found from a simulation run. Points of the Valve Performance Curve in the orifice flow model can, therefore, be directly calculated from one simulation run.

Throttling flow, however, is more complicated to describe since the valve stem assumes its equilibrium position as the result of the different forces acting on the stem. These forces come from the dome charge and the injection pressures acting on their respective surfaces in addition to the net force acting on the valve stem tip. Since CFD calculations require the knowledge of the actual valve stem travel in order to calculate the pressure distribution and consequently the net force arising on the valve stem tip, finding the points of the Valve Performance Curve in throttling flow requires an iterative procedure.

The iterative solution is based on the fact that at equilibrium conditions the sum of the forces acting on the valve stem is zero. There are four forces involved: (1) the dome charge pressure acting on the full bellows area, (2) the spring force arising in the metal bellows, (3) the net force acting on the valve stem tip, and (4) the injection pressure acting on the difference of the bellows and port areas.

The sum of the two first forces tries to close the valve; they can be calculated from the formula given in the following. As seen, both the increase in dome charge pressure due to compression of the bellows and the increase of spring force due to the increase of valve travel are properly considered.

$$F_c = \frac{p_{d1} V_{d1}}{V_{d1} - x\, A_b} A_b + k\, x \qquad \mathbf{6}$$

The two latter forces try to open the valve and are easily found from CFD calculations and from the injection pressure. By setting the opening and closing forces equal, the valve's actual stem travel is found; this is the principle of the iterative procedure developed.

Using the procedure detailed, one can easily develop Valve Performance Curves of any gas lift valve for any conditions. Two sample curves for the CAMCO BK-1 valve with a 3/16 in. port and a dome charge pressure of 67 bars are given in **Figs. 6** and **7**. Both figures present gas injection rates calculated from CFD simulations as well as those found from the **API RP 11V2** [9] model. **Fig. 6** involves orifice flow with an injection pressure of 82.7 bars, while **Fig. 7** shows the valve performing in the throttling region at an injection pressure of 72.6 bars.

CONCLUSIONS

1. Computational Fluid Dynamics (CFD) techniques can be used to investigate the gas throughput capacity of gas lift valves.
2. The proper description of the flow space inside a gas lift valve has a high importance on the accuracy and the required run time of CFD calculations.
3. The simplified cell structure suggested in the paper permits reasonable run times while ensuring proper accuracy.

4. Gas lift performance curve data developed from CFD calculations compare favorably with those found from **API RP 11V2** calculations.

LIST OF SYMBOLS

A_b	= effective bellow area
F_c	= sum of valve closing forces
Q_g	= gas injection rate through the gas lift valve
V_{d1}	= volume of valve chamber at zero valve stem travel
$\vec{g}$	= acceleration of gravity
h	= enthalpy
k	= spring constant of the unloaded bellows assembly
p	= pressure
p_{d1}	= bellows charge pressure at zero valve stem travel
p_p	= production pressure
p_i	= injection pressure
t	= time
$\vec{v}$	= fluid velocity
x	= valve stem travel
λ	= heat transfer coefficient
μ	= dynamic viscosity
ρ	= density of flowing fluid
ζ	= bulk viscosity

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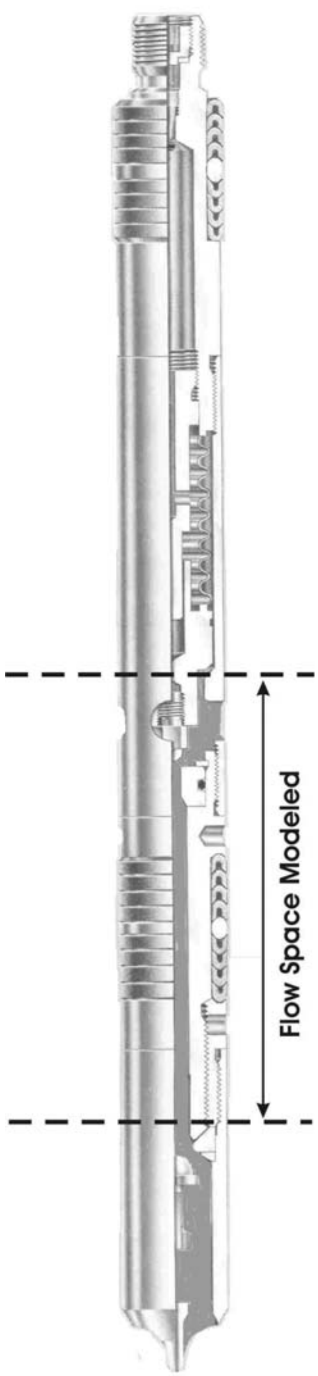

Figure 1- The flow space modeled in the gas lift valve.

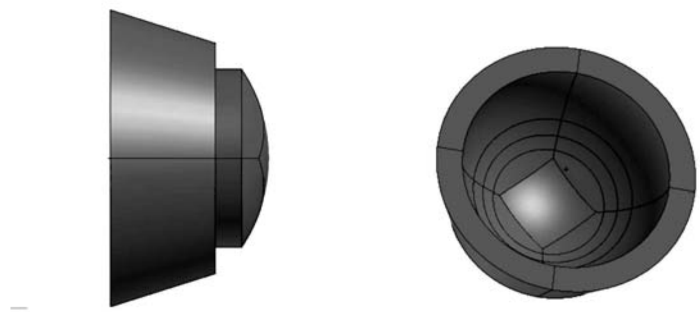

Figure 2 - Construction of the flow space around the valve stem tip.

Figure 3 - Original representation of the flow space.

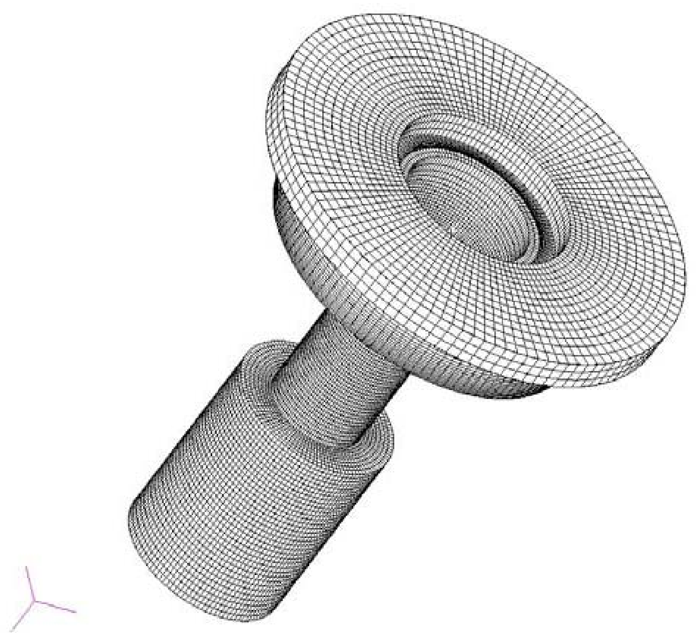

Figure 4 - The final cell structure of the flow space.

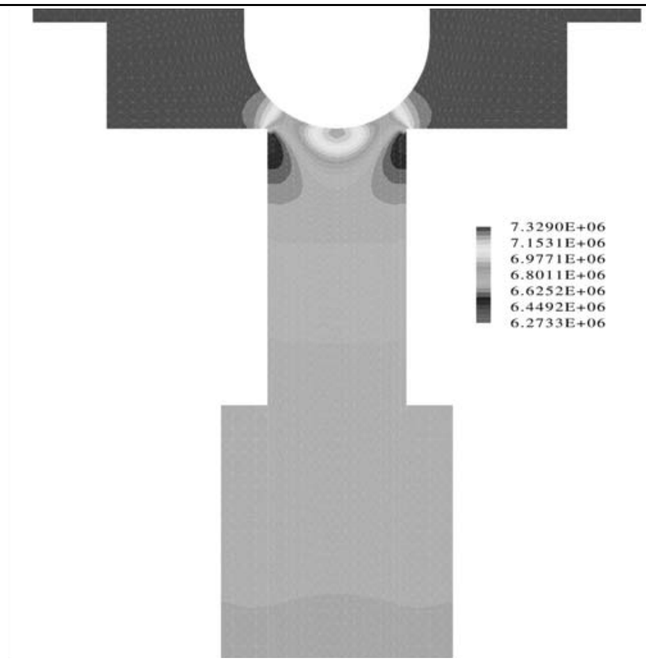

Figure 5 - Example pressure distribution inside a gas lift valve.

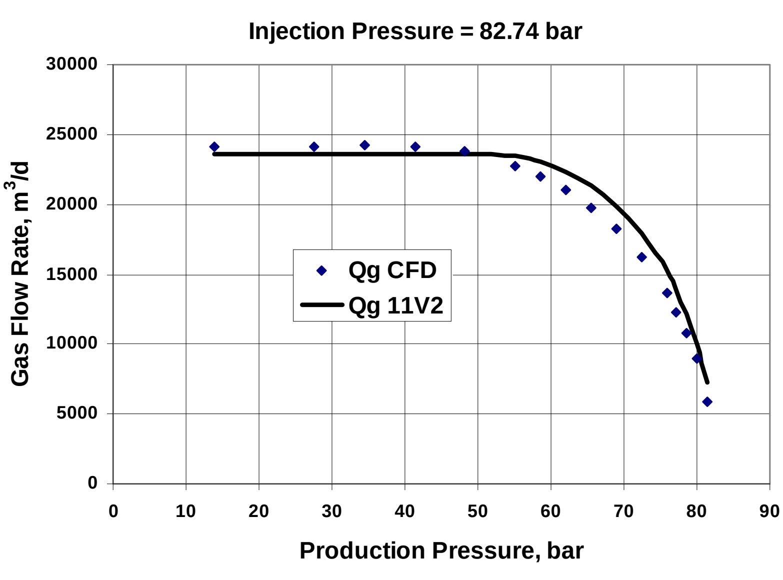

Figure 6 - Sample Valve Performance Curve for orifice flow.

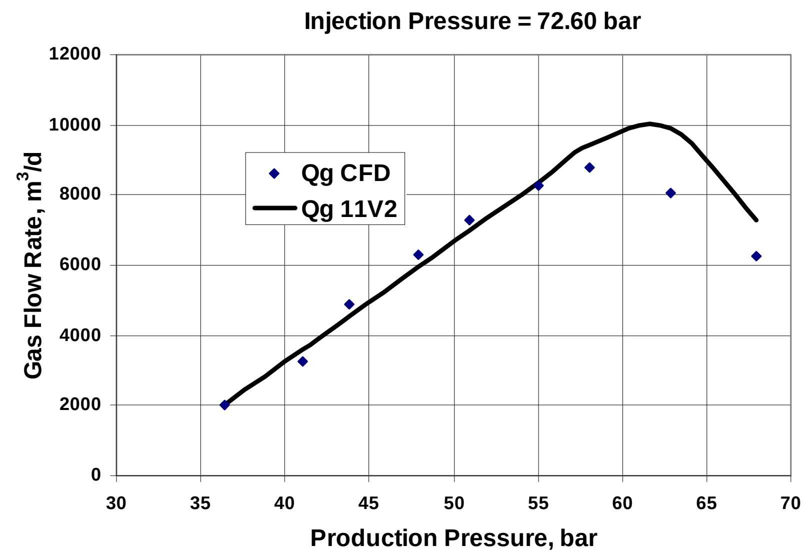

Figure 7 - Sample Valve Performance Curve for throttling flow.