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Hydraulic Force Modeling of Radial Jet Drilling

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Abstract

Radial jet drilling (RJD) is a stimulation method to increase reservoir contact while utilizing existing infrastructure and wellbores. RJD exploits a calling within the industry by targeting marginal reservoirs, thin pay zones, heavy oil reservoirs, coal bed methane, low-permeability reservoirs, and old, conventional, low-producing reservoirs. Development of the RJD technology has led to a small diameter, multi-orifice nozzle, which generates a cutting force (i.e. jet impact force) to penetrate the formation rock and a propulsion force to advance the bit into the formation. Many of the previous studies focus on improving the technology and implementation, but just a handful concentrate on modeling propulsion force to provide reasonable predictions. However, the models require empirically determined parameters to provide an accurate prediction of the propulsion force.

This paper presents a generalized propulsion force model, centered on mass, momentum, and energy conservation equations. The model incorporates a discharge coefficient correlation for multi-orifice nozzles to determine the impact and propulsions force generated at each orifice. The predictions of the new model compared with existing models and new measurements and display an acceptable agreement.

Introduction

The concept of radial jet drilling (RJD), through advances in research and technology, have proven successful in various applications around the world. RJD uses high-pressure water jets to cut through rock with back jets to propel the bit into the formation. This technique involves drilling multiple small diameter laterals from a single vertical wellbore to increase reservoir contact (Kohar and Gogoi 2014). The laterals bypass the near wellbore skin or any accumulated damage around the wellbore to reach previously untouched part of the formation and acting as a conduit for reservoir fluids.

The existing hydraulic force models (Ruichange et al. 2009; Li et al. 2015) require experimentally derived variable to provide accurate predictions. Without accurate model predictions, operators tend to shy away from such uncertainty, especially with little room for error working in depleted or marginal reservoirs. This study seeks to generate a general RJD hydraulic force model built on established conservation laws to determine working pressure and subsequent flow rates throughout an operation.

The goal of this study is to develop an improved and generalized model. The objectives of this analysis include:

- Understand the hydraulic forces of a jetting nozzle
- Generate a general force model to predict propulsion for multi-orifice nozzles accurately
- Investigate discharge coefficients of jetting nozzles and develop a concise correlation or model

The method for this study contains a literature review, theoretical modeling, experimental inquiry and theoretical analysis. Previous literature covers essential information required for a basic understanding of RJD hydraulics by laying the groundwork for the aspects that are going into the RJD concept. Theoretical modeling develops a prediction method of hydraulic forces with improvement stemming from the comparison with experimental data. An analysis evaluates the accuracy and leads to ideas for improving the RJD design and application in the field.

Literature Review

The literature review touches on the development of the RJD system, field studies focusing on the capability of the system and the improvements in production, and the theories that go into the RJD application.

System Development

Like most technology, RJD started with a humble beginning, relatively bulky and robust. Through research along with some trial and error, the system became improved reducing cost, risk, and time while becoming more applicable and user-friendly. The early life of RJD targeted shallow heavy oil reservoirs with multiple lateral holes at the same depth equipped with a 1.25-inch production tube extending 100–200 ft into unconsolidated formations. One major breakthrough with RJD, the ultra-short radius concept, in which the wellbore deviates from vertical to horizontal with a 10-12 inch radius curve, eliminating underreaming. Another discovery included the development of the self-regulated propulsion system as a function of the internal fluid pressure. The front-facing nozzles create strong jet impact force to cut into the rock, while backward-facing nozzles generate adequate propulsion force to overcome the reaction force developed by the front nozzles and mechanical friction. The high pressure and propulsion forces keep the hose and bit in tension, drilling a straight hole (Dickinson and Dickinson 1985).

The next improvement came with the development of an erectable whipstock equipped with internal rollers, reducing the friction when running around the short radius curve, displayed in **Fig. 1** (Dickinson et al. 1986). Later came the integration of the control while drilling system (CWD) which consists of four side jets monitored by an electric pilot and deploying a real-time electromechanical inclinometer to compensate for the rolling of the bit by distributing power with a set of solenoids (Dickinson et al. 1990).

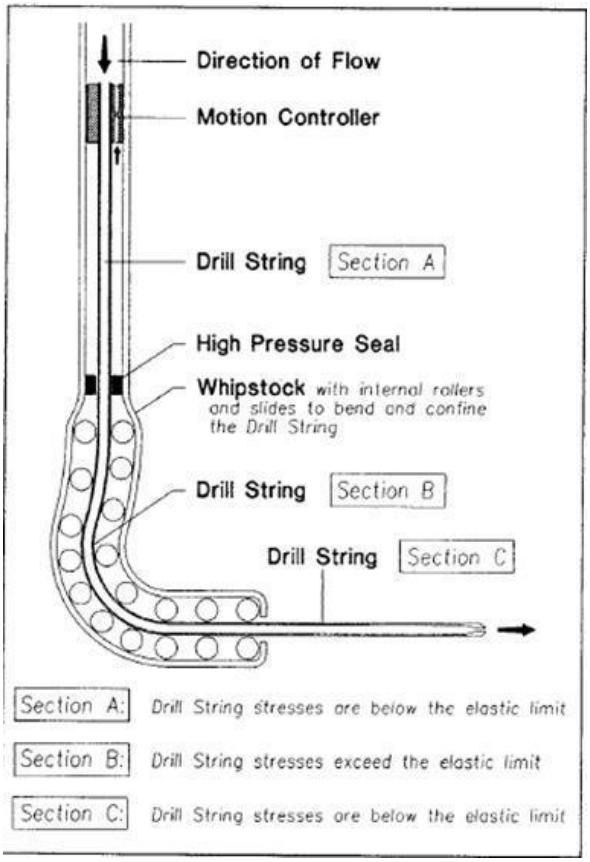

Fig. 1 – Schematic of the early RJD system (Dickinson et al. 1986)

Continued improvement of the RJD system leads to a reduction in hole size from 4-inch to 1.5-inch and hose size from 1.25-inch to 0.5-inch, which reduces the fatigue and strain on the pipe. These improvements guide the system commonly used today consisting of a coiled tubing unit, downhole filter, production tubing (already in place), diverter shoe, flexible hose, and the jetting bit displayed in **Fig. 2** (Buckman et al. 2013). The key system upgrades include a high strength flexible hose made from braided Kevlar or similar material (Bruni et al. 2007) and the 1-inch diameter jet bit consisting of one to three forward facing nozzles coupled with five or six backward-facing nozzles.

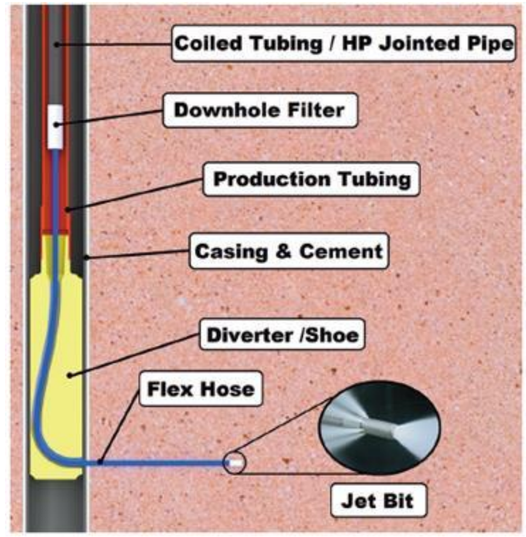

Fig. 2 – BHA of the Buckman Jet Drilling system (Buckman et al. 2013)

Field Studies

With several field application studies conducted, two key analyses display the potential of implementing RJD to enhance production. The first study (Cinelli and Kamel 2013) was performed in the marginal Donelson West field in Cowley County, Kansas. The gas driven formation is predominantly carbonate rock with a permeability of 1-10 md, porosity between 15-20%, and pay thickness of 6-10 ft. A target formation this thin makes conventional horizontal drilling and completion techniques uneconomical. The primary difference in this study was performing an acid frac after jet drilling the laterals with production data provided in **Table 1** before and after stimulation. The acid reacts with the formation creating an even greater contact area with the producing formation, but which had a greater influence on the increased production, the RJD or the acid frac? This study contains nearly ideal conditions to examine the efficacy of RJD, but the addition of the acid frac leaves a level of uncertainty.

Table 1 – Production data before and after RJD (data from Cinelli and Kamel 2013)

Pre-RJD		Post-RJD			
			Total Monthly Field Production	Old wells total monthly field production	Average monthly production per well
Year	bbl/month	Months after	bbl/month	bbl/month	bbl/month
2002	11	1	1100	231	33
2003	62	2	974	244	35
2004	125	3	976	234	33
2005	106	4	961	248	35
2006	85	5	789	221	32
2007	70	6	790	213	30
2008	133	7	1124	475	68
2009	142	8	797	247	35
2010	197	9	803	265	38
Average ('08-'10)	157	Average	924	264	38

The other key study that displays the influence on production comes from Buckman et al. (2013) in which shallow pay zones jet drilled 8 to 16 laterals 4 to 40 feet in length. The data in **Table 2** shows production before and after RJD operations. Although the percent increase in production looks great, the initial production rates were small, and this does not necessarily indicate the economic viability of the RJD operation.

Table 2 – Pre and Post RJD production data (courtesy of Dr. Buckman with BJD)

Depth (feet)	Average Penetration (feet)	# of Laterals	bopd Pre SRS	bopd Post SRS tot	Pre/Post
1750	40	12	1	20	2000%
1240	30	16	5 mcfd	80 mcfd / 2 bopd	1600%
337	4	12	0	2 bopd	>200%
730	12	12	0	20 bopd / fracture	>200%
1310	12	16	0	14 bopd	>1000%
1200	20	16	0	12 bopd	>1000%
1200	14	16	0	3 bopd	>200%
1310	20	16	0	2 bopd	>200%
Sheath System					
1237	20	8	1	3 bopd	300%
780	15	8	0.75	2.75	360%
1035-1038	15	8	0.5	1	100%
1150	15	8	0.25	0.5	100%
748	12	8	1.5	0.5	30%
1240	12	15	0.25	2.75	900%
1755-1759	16	8	2.5	3 3/4	100%
1740-1744	16	8	2.5	3 3/4	100%

Theoretical Studies

Many different studies have looked into the various aspects that go into RJD from penetration mechanisms to cavitation within orifices. With increasing the contact area as the primary goal, Bruni et al. (2007) indicated four penetration mechanisms: poroelastic tensile failure, erosion at the surface, fracturing, and cavitation. Each factor into the rock breaking capacity of the jet bit, but this is only one aspect of the entire process. With the rock breaking into small fragments typically called cuttings, which may settle in the bottom of the lateral the friction with the hose will increase, reducing the drillable lateral length. Understanding the working environment of RJD helps to design, study, and prioritize the elements that go into improving the system. In the case of RJD, pressure, cuttings transport, rock type, and the ability to cut the rock are factors more affected by the environment.

Factors impacted more by the design of the RJD system include propulsion force, friction on the hose, aspect ratio, and discharge coefficient. Propulsion force, a key factor in ROP depends on flow rate, orifice diameter, orifice angle, and number of orifices in the jet bit (Chi et al. 2016). The propulsion force must overcome the cutting force and friction, but cannot be so great to outrun the rate of penetration. The propelling force is a function of flow rate or pressure, nozzle diameter, nozzle angle, number of nozzles, and discharge coefficient. The higher the flow rate or pump pressure, the more force is generated, which makes sense. From Chi et al. (2016) the optimum number of back facing nozzles found to be five or six with an optimum angle ranging from 12.5° to 22.5°. The nozzle diameter affects the by an increased fluid exit velocity with a decrease in diameter. Decreasing the diameter of the nozzle also changes the aspect ratio of length over diameter, which subsequently change the discharge coefficient. The optimum aspect ratio for the optimum discharge coefficient is around two, according to data gathered from Ward-Smith (1971) and Lichtarowicz et al. (1965). From Ramamurthi and Nadakumar (1999) an aspect ratio around five has the tendency to onset cavitation at the end of the nozzle decreasing the discharge coefficient.

Modeling

The goal of an RJD force model seeks to predict forces encountered when operating in the field accurately and efficiently. Models use previous data and as few assumptions to formulate a calculation within an acceptable margin of error. This is tough for RJD with the vast amount of uncertainty downhole, but with more data comes less doubt within the model. Two such models derived from both the momentum and energy balance equations provide a reference and comparison when creating a new model.

Theoretical Model 1

The first model comes from Ruichange et al. (2009) and functions through momentum balance. Referring to **Fig. 3**, P_{in} and P_{out} represent inlet and outlet pressures of the jet bit. A_{in} and A_{out} refer to the inner and outer sectional areas of the bit. Q_{in} and Q_{out} denote flow rates of the forward and backward jets. V_{front} and V_{back} represent the flow velocities of the forward and backward jets, with v_{in} being the flow rate in the hose, and θ is the angle between the center axis of the backward nozzles and the jet bit.

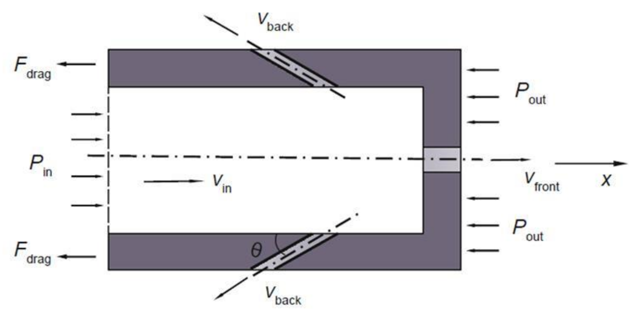

Fig. 3 – Simple nozzle illustration of the forces in the system (Ruichang et al. 2009)

The experiments conducted in this study looked into the pulling force, the pressure drop across the bit, and annular pressure loss. The experiment used a single forward jet with three nozzle diameters of 30, 40, and 50 mm flowing between .1 and 2.0 L/s. **Fig. 4** shows a parabolic trend of flow rate versus pressure drop with both theoretical values and experimental data plotted. Ruichang et al. (2009) also noted the relation of a decrease in differential pressure coefficient with an increase in hole diameter, displaying a linear relationship with flow rate. All three hole diameters exhibited a parabolic trend of flow rate versus pulling force being within 3% margin of the corresponding theoretical calculation. Although, the data of the 30, 40, and 50 mm hole size are virtually identical and lie on top of one another when plotted on the same graph. At the same flow rate, the pulling force should change with a change in diameter.

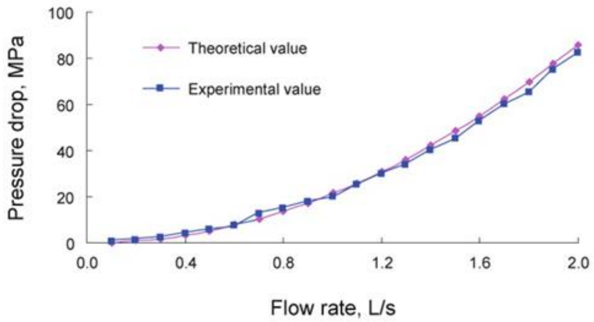

Fig. 4 –Pressure drop vs. flow rate (Ruichang et al. 2009)

Theoretical Model 2

The other model developed by Li et al. (2015) stems from a study of the multi-orifice nozzle propulsion forces. The study looked into design variations of the bit nozzle and the resulting effects on the forces. **Fig. 5** shows a simplified illustration of the bit nozzle consisting of a center nozzle, forward nozzles, and backward nozzles.

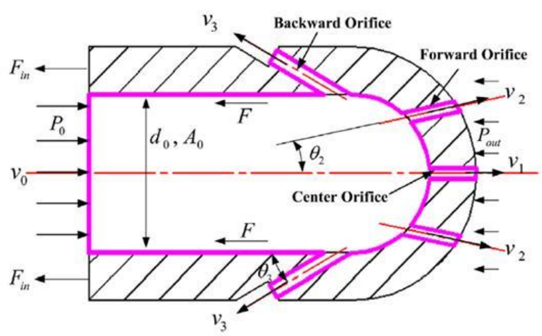

Fig. 5 – Design of a multi-orifice nozzle (Li et al. 2015)

The model functions on four key assumptions; the working fluid is incompressible, the velocity of the fluid at each orifice is equal to the average velocity, the flow is steady, and the bit orientation is considered horizontal. The model operates on the axial momentum equation to calculate the self-propelling force and a summation of forces to obtain the net force. F_{in} refers to internal force on the bit, while F_{sp} is the self-propelled force in N, Q_0 is the incoming flow rate in L/s, A_0 is the cross-sectional area of the nozzle in mm^2, ρ is fluid density in kg/m^3, and m is the self-propelling dimensionless factor of the nozzle. According to the study, the m factor obtained experimentally and used in conjunction with discharge coefficient to find the self-propelling force. This study also used an apparatus to obtain the discharge coefficient and flow ratio experimentally.

The plot in **Fig. 6** displays the comparison of measured force and calculated force on a flow rate versus self-propelled force chart. The maximum difference of 4% between calculated and measured values indicates accurate force prediction. Li et al. validated the model from studying the 6+3+1 nozzle configuration, being 6 backwards nozzles, 3 forward nozzles, and 1 center nozzle, with numerical and calculated values displayed in **Table 3**. For cases number 1 through 5 use a discharge coefficient value of 0.72 and flow coefficient value of 0.75. This model also offers a comparison, but pose some questions in the calculation process. Replicating the same calculations proved difficult without further explanation of the discharge coefficient used. That said, this offers good insight into the tendencies of the jetting bit, while still leaving areas of improvement.

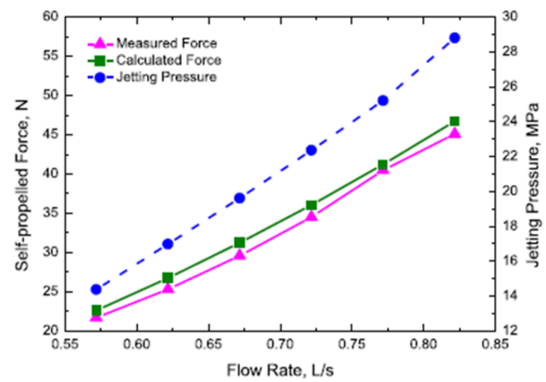

Fig. 6 – Measured and calculated self-propelling force versus flow rates (Li et al. 2015)

Table 3 - Numerical and calculated propulsion force (Li et al. 2015)

No.	Q_0, L/s	P_0, Mpa	F, N	F_{in}, N	F_{sps}, N	F_{spc}, N	Error %
1	0.785	9.7	768.6	736.6	35.0	32.0	9.5
2	0.942	14.0	1106.6	1059.3	49.8	47.3	7.7
3	1.178	21.6	1723.7	1651.2	78.3	72.5	9.2
4	1.414	31.2	2481.6	2375.0	113.1	106.6	7.0
5	1.571	38.1	3056.4	2925.5	139.6	131.0	7.3

New Model

To formulate a new model using the same illustration from Ruichang et al. (2009), the control volume boundary is represented with the red dotted (**Fig. 7**). The new model is based on reasonable assumptions including: incompressible fluid, steady isothermal flow, the characteristics of orifices are like that of nozzles, and wall shear stress is negligible. The model utilizes the principals of mass conservation, energy balance, and momentum conservation.

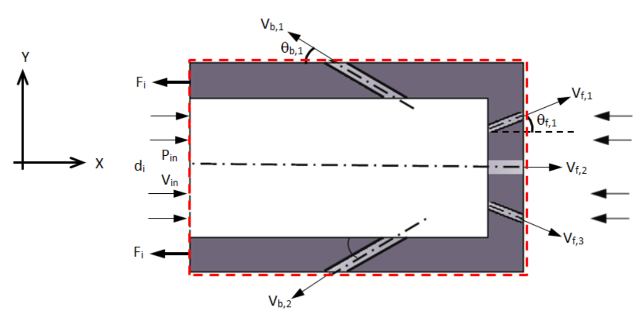

Fig. 7 – Forces on the jet bit (adopted from Ruichang et al. 2009)

The conservation of mass describes the accumulation rate of mass as the sum of mass flow entering the control volume and the sum of the mass leaving the control volume. With the assumption of steady flow the rate of accumulation becomes zero, thus the mass in is equal to the mass out shown in **Eq. 1**.

$$Q = A_{in}V_{in} = A_{f,1}V_{f,1} + A_{f,2}V_{f,2} + A_{f,3}V_{f,3} + A_{b,1}V_{b,1} + A_{b,2}V_{b,2} \quad \textbf{(1)}$$

The linear momentum equation incorporates the Reynolds transport theorem by differentiating the linear momentum. Analogous to the mass flow rate, applying the momentum flux terms provides a generalized equation for one-dimensional uniform velocity inlets and outlets and reduces to the propulsion force equation given in **Eq. 2**.

$$F_{propulsion} = -\dot{m}_{f,1}V_{f,1}Cos(\theta_{f,1}) - \dot{m}_{f,2}V_{f,2}Cos(\theta_{f,2}) - \dot{m}_{f,3}V_{f,3}Cos(\theta_{f,3}) + \dot{m}_{b,1}V_{b,1}Cos(\theta_{b,1}) + \dot{m}_{b,2}V_{b,2}Cos(\theta_{b,2}) + (\dot{m}_{in}V_{in}) \quad \textbf{(2)}$$

For isothermal flow, the energy balance of generalized incompressible fluid can be simplified for nozzle flow by neglecting kinetic energy head, losses due to friction, and elevation change. Accounting for the viscous effect of the fluid, the nozzle outlet velocity equation is expressed as:

$$V_{out} = C_d\sqrt{\frac{2(p_0 - p_{out})}{\rho}} \quad \textbf{(3)}$$

The discharge coefficient (C_d) strongly correlates to the aspect ratio (length divided by the diameter of an orifice), given by a series of three equations for three ranges of aspect ratios (Morris and Garimella (1998). To simplify the calculation, data provided by Ward-Smith (1971) and Morris and Garimella (1998) used to create a discharge coefficient equation valid for wide ranges of aspect ratios (0 to 9.5) and Reynolds numbers (4000 to 100,000).

$$C_d = 0.000067536\left(\frac{L}{d}\right)^5 - 0.00200928\left(\frac{L}{d}\right)^4 + 0.0227695\left(\frac{L}{d}\right)^3 - 0.121037\left(\frac{L}{d}\right)^2 + 0.2867\left(\frac{L}{d}\right) + .56623 \quad \textbf{(4)}$$

Experimental Study

The goal of the experiment study is to validate the new RJD force model. Data collection involves flow rate, pressure, and force. The model calculations require pressure, thus recording the flow rate along with pressure allows comparison of measurements with model predictions. The resultant force varies with change in flow rate and pressure.

The test set up shown in the schematic in **Fig. 8**, utilizes the following components: i) constant water source; ii) pump to increase fluid pressure; iii) two high-pressure hoses to withstand operating pressures; iv) high pressure ball valve; v) flow meter; vi) pressure gauge; vii) pressure sensor; viii) force sensor; ix) clear tubing to contain the water; and x) water collection bucket equipped with drain hose.

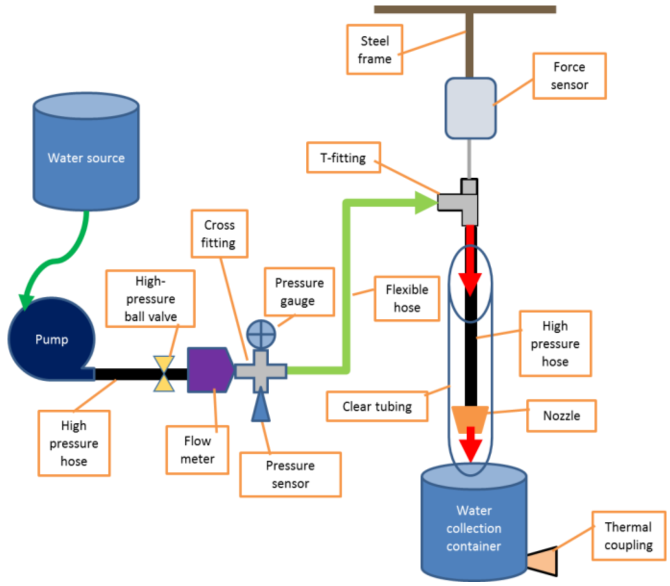

Fig. 8 – Test loop schematic

With electronics and other components working properly, the experiment begins by turning on the water allowing the system to fill with water removing air from the system. With the system removed of air, start the pump while monitoring sensors and gauges to ensure proper function. The flow rate and force reading are collected, followed by throttling the ball valve to reduce flow and again waiting for the flow to stabilize and record the data. The flow is reduced until the meter displays zero, then the ball valve is opened fully and the force reading is monitored to see the return of the initial value. **Fig. 9** presents the data and model predictions. The two trends maintain the same slope with a margin of error less than 2%, only differing by six-tenths of a Newton at most.

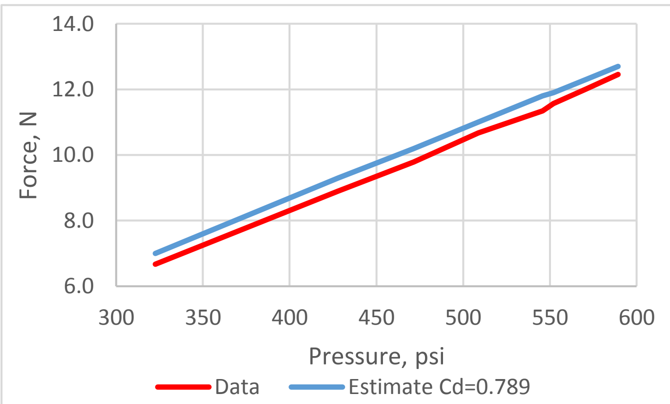

Fig. 9 – Calculated vs experimental data plotted pressure to force

With the data and model predictions this similar, a slight variation in the discharge coefficient to 0.78 renders the data and theoretical calculation nearly identical. This shows the model as an adequate representation and useful for force calculation in designing RJD system. Ignoring pressure losses due to pipe friction or diameter changes in the flow path before the bit may explain the 0.009 difference in discharge coefficient.

Conclusions

This theoretical and experimental study sought to develop a general hydraulic force model to predict operating forces for RJD bits. With many factors influence the system, simplification of some calculations and leaving the model flexible to various designs helped to build a generalized model. The implementation of the discharge coefficient improved the model and eliminates the need for additional empirical parameters. The key contributions of this study include:

- Development of an adequate generalized propulsion force model.
- Presenting discharge coefficient that accounts for nozzle geometry.
- Determine the effects of pressure and flow rate on the RJD performance.
- Generate experimental data for comparison.
- Demonstrate the validity of the force model.

Acknowledgments

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Nomenclatures

BHA = *Bottomhole assembly*
RJD = *Radial jet drilling*
C_d = *Discharge coefficient*
P_0 = *Inlet pressure*
P_{out} = *Discharge pressure*
F_{in} = *Inlet force*
F_{sp} = *Self-propel force*
F_{sps} = *Numerical self-propel force*
F_{spc} = *Calculated self-propel force*
$F_{propulsion}$ = *Propulsion force*
F = *Total force*
Q = *Flow rate*
L = *Orifice length*
d = *Orifice diameter*
L/d = *Aspect ratio (length divided by diameter)*
v_0 = *Initial fluid velocity*
$v_{1,2,3}$ = *Fluid discharge velocity for denoted orifice*
V_{out} = *Fluid discharge velocity*
ρ = *Density*
A_{in} = *Inlet cross sectional area*
$\dot{m}_{f,n}$ = *Mass flow rate*

References

1. Bruni, M.A., Biasotti, J.H., and Solomone, G.D. 2007. Radial Drilling in Argentina. Presented at the Latin American & Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina, 15—18 April. SPE-107382. http://dx.doi.org/10.2118/107382.
2. Buckman, W.G., Buckman, Z.P., and Maurer, W.C. 2013. A new approach to drilling. Hydrocarbon Engineering, Oilfield Technology 2 (8): 37—40.
3. Chi, H., Li, G., and Liao, H. 2016. Effects of parameters of self-propelled multi-orifice nozzle on drilling capability of water jet drilling technology. 86, International Journal of Rock Mechanics and Mining Sciences: 23—28. http://dx.doi.org/10.1016/j.ijrmms.22016.03.017.
4. Cinelli, S.D. and Kamel, A.H. 2013. Drilling Contractor. Low-cost radial jet drilling helps revitalize 40-year-old oilfield, http://www.drillingcontractor.org/low-cost-radial-jet-drilling-helps-revitalize-40-year-old-oilfield-23377(accessed 12 December 2015).
5. Dickinson, W. and Dickinson, R.W. 1985. Horizontal Radial Drilling System. Presented at the SPE California Regional Meeting, Bakersfield, California, 27—29 March. SPE-13949. http://dx.doi.org/10.2118/13949
6. Dickinson, W., Anderson, R.R., and Dickinson, R.W. 1986. The Ultrashort-Radius Radial System. Presented at the IADC/SPE Drilling Conference, Dallas, Texas, 10—12 February. SPE-14804. http://dx.doi.org/10.2118/14804.
7. Dickinson, W., Pesavento, M.J., and Dickinson, R.W. 1990. Data Acquisition, Analysis, And Control While Drilling With Horizontal Water Jet Drilling Systems. Presented at the International Technical Meeting, Calgary, Canada, 10—13 June. SPE-90-127. http://dx.doi.org/10.2118/90-127.
8. Kohar, J.P. and Gogoi, S. 2014. Radial Drilling Technique For Improving Recovery From Existing Oil Fields. International Journal of Scientific & Technology Research 3 (11): 159—161.
9. Li, J., Li, G., and Huang, Z. 2015. The self-propelled force model of a multi-orifice nozzle for radial jet drilling. Journal of Natural Gas Science and Engineering (24) 441—448.
10. Lichtarowicz, A., Duggins, R.K., and Markland, E. 1965. Discharge Coefficients for Incompressible, Non-Cavitating Flow through Long Orifices. Journal of Mechanical Engineering Science 7 (2): 210—219. http://dx.doi.org/10.1243/JMES_JOUR_1965_007_029_02.
11. Morris, G.K. and Garimella, S.V. 1998. Orifice and Impingement Flow Fields in Confined Jet Impingement. ASME Journal of Electronic Packaging 120 (1): 68—72. http://dx.doi.org/10.1115/1.2792288.
12. Ramamurthi, K. and Nandakumar, K. 1999. Characteristics of Flow through Small Sharp-Edged Cylindrical Orifices. Flow Measurement and Instrumentation 10 (3): 133—143. http://dx.doi.org/10.1016/S0955-5986(99)00005-9.
13. Ruichang, G., Gensheng, L., and Zhongwei, H. 2009. Theoretical and experimental study of the pulling force of jet bits in radial drilling technology. Petroleum Science 6 (4): 395—399.
14. Ward-Smith, A.J. 1971. Pressure Losses in Ducted Flows. In A Unified Treatment of the Flow and Pressure Drop Characteristics of Constructions Having Orifices with Square Edges Chapt. 4. London, United Kingdom: Butterworths.