CONTROL OF FLOW RATE IN HEAVY-OIL PIPELINES USING PID CONTROLLER

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Abstract. Along with the development of urbanization and the needs of the industry, more and more trunk oil pipelines are being built and serviced. For this industry, more reliable, effective and flexible control systems for the automation of the oil pipeline system are needed to prevent leaks during transportation. PID controller is used to control the flow rate of heavy oil in pipelines by controlling the vibration in the motor pump. Torsion actuator is installed on the motor pump to control the vibration in the motor and thus control the flow rate in the pipelines.
Keywords: *PID controller, motor pump, open-loop model, linear model.*

1. Introduction

Oil pipelines and transfer pump units are critical parts of the oil transportation system because they can interfere with daily production, cause property losses and even damage the environment due to pipeline leaks, abnormal operation of energy-mechanical system equipment with certain faults. With the development of advanced technology, fault diagnosis systems, leak detection systems in the control center, safety control and physical parameter control, etc. are installed in the pipelines. The distance between the shut-off valves is optimal. The component of the protection system should be selected according to the cross-section through which the pipelines pass, so as to regulate the pressure, flow rate and flash point of petroleum products and prevent cracks from occurring in the pipelines. PID control is used to control and maintain processes. PID is simply an equation that the controller uses to evaluate the variables being controlled. The process variable is measured and a feedback signal is sent to the controller. The controller then compares the feedback signal with the one sent and generates an error value. The value is checked using one or more of three proportional, integral and derivative methods. As a result, the controller issues the necessary command or changes the control variable to correct the error [1].

PID controllers use feedback control in industrial applications and control systems. The controller first calculates an error value as the difference between the measured process variable and the preferred set-point value. It then attempts to minimize the error by increasing or decreasing the process control inputs or outputs so that the process variable approaches the target value. This method is most useful when the mathematical model of the process or control is too complex or unknown to the system. To improve performance, for example by increasing the responsiveness of the system, the PID parameters must be tuned to suit the specific application.

2. Problem statement

This paper deals with modeling and control of flow rate in heavy oil pipelines. For this purpose, PID control algorithm is used to control the flow mechanism in pipelines. Torsion bar drive is installed in the motor pump to control vibration in the engine. The stability of the PID controller is tested using Lyapunov stability analysis. Analysis of the stability of the controller leads to a theorem that confirms that the state system is limited. Theoretical concepts are tested by numerical simulation and analysis that prove the effectiveness of the PID controller in controlling flow rates in pipelines [2].

The flow control system is a feedback control system. The structure of the pump model is explained in Figure 1, it is an open-loop system. If there is unwanted vibration in the motor, the flow stability will be disturbed. Therefore, it is important to convert the open-loop system into a closed-loop system by applying a controller that controls the flow stability by controlling the vibration in the motor.

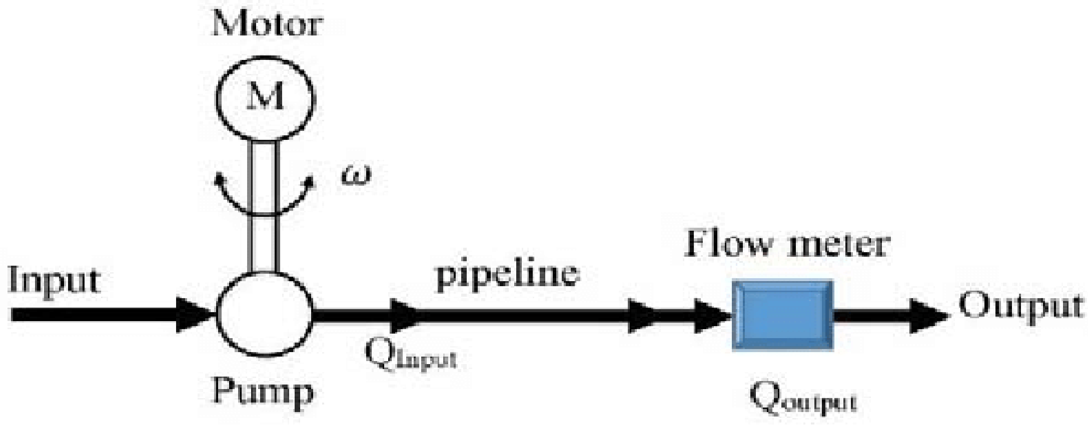

Figure 1. Open-loop model scheme.

3. Pipe modelling

Linear global flow stability theory is based on self-decomposition of linearized flow operators. Direct and adjoint decompositions associated with such operators provide information on the stability of the operator, the acceptance of initial conditions and external forcing, and the sensitivity to spatially localized disturbances [5]. For an incompressible liquid, the distribution is constant. We suggest that you obtain the simplest form of the operation by setting the density type equal to zero and dividing by the constant ρ:

$$\frac{\partial u}{\partial t} = -\frac{\Delta p}{\rho} - u.\nabla u + F_f \tag{1}$$

where, ρ-is the density in $\frac{kg}{m^3}$, Δ-divergence, u-is the flow velocity, p-is the pressure, t is the time in s, F_f- is termed as the summation of external force and body forces [1].

Introducing the mass balance into equation (1), the following conclusion can be described:

$$\nabla.u = 0 \tag{2}$$

Equation (1) can be described as,

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + F_f \tag{3}$$

where $\frac{\partial p}{\partial x}$- is the change of pressure in two different points, to achieve numerical stability of calculations.

$$\frac{\partial u_i}{\partial t} = -\frac{1}{\rho L}(p_i - p_{i+1}) + F_f, i = 1 \dots. n \tag{4}$$

where L- is taken to be the distance between two sections. Now let's mention pressure coefficient

$$\alpha p_i = p_{i-1},\ i = 1 \dots. n \tag{5}$$

where, α- is termed as the coefficient of pressure changes in sections

$$\frac{\partial u_i}{\partial t} = -\frac{1}{\rho L}(1-\alpha)p_i + F_f, i = 1 \dots. n \qquad (6).$$

The friction loss under laminar flow conditions is given with the Hagen-Poiseuille equation. By taking into consideration a fluid of density (ρ) and kinematic viscosity v, the hydraulic slope F_f can be described as,

$$F_f = \frac{64}{Re} \frac{u^2}{2gD} + F_b = \frac{64vu}{2gD^2} + F_b \,, \tag{7}$$

where g- is the gravity, D-is pipe diameter and F_b –is the shape force vector in pipes. If some substitutions are made, equations (7) will be as following:

$$\frac{\partial u_i}{\partial t} == -\frac{1}{\rho L}(1-\alpha)p_i + \frac{64vu}{2gD^2} + F_b \,, i = 1 \dots . n \tag{8}$$

By taking into consideration $F = ma = m\frac{d^2x}{d^2t}, u = \frac{dx}{dt}$, equation (8) will be as below:

$$\frac{\partial}{\partial t} \frac{\partial x_i}{\partial t} = -\frac{(1-\alpha)}{\rho AL} \frac{\partial^2 x_i}{\partial t^2} \tag{9}$$

Therefore,

$$-\frac{(1-\alpha)}{\rho AL} \frac{\partial^2 x_i}{\partial t^2} + \frac{64v}{2gD^2} \frac{\partial x_i}{\partial t} \tag{10}$$

4. Linear model of torsion actuator

Control valves must provide reliable and repeatable control of the process fluid over a wide range of operating conditions. The control valve flow characteristic represents the dependence of the relative flow rate through the valve on the relative stroke of the control valve while maintaining a constant pressure drop.

Linear flow characteristic – equal increases in the relative stroke of the valve result in equal increases in the relative flow rate. Regulating valves with linear flow characteristic are used in systems where there is a direct relationship between the regulated value and the medium flow rate. Regulating valves with linear flow characteristic are ideal for maintaining the temperature of the mixture of heat carriers in heating stations with dependent connection networks [5].

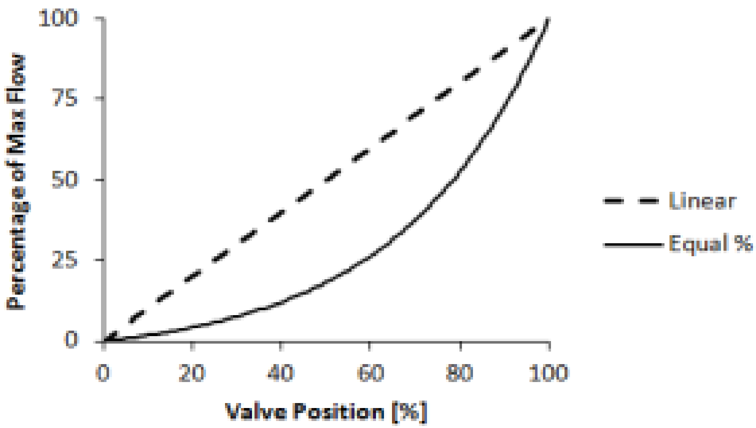

Figure 2. Linear model of torsional actuator

5. PID structure

PID controller is a well-known and most commonly used controller in industrial applications because PID controller is simple, provides good stability and fast response. In each application, the gains of these three actions are changed to obtain the optimum response and control. The input signal of the controller is the error signal, and the output signal is given to the process. The output signal of the controller is shaped in such a way that the output signal of the process tends to reach desired value.

PID controller is a closed-loop feedback system that compares a process variable with a set-point and generates an error signal according to which it regulates the output of the system. This process continues until this error becomes zero or the value of the process variable becomes equal to the set-point.

PİD controllers are designed based on the microprocessor technology. Different manufactures uses different PİD structures. The most commonly used PİD equations are parallel which parallel type design of controller is used in this article.

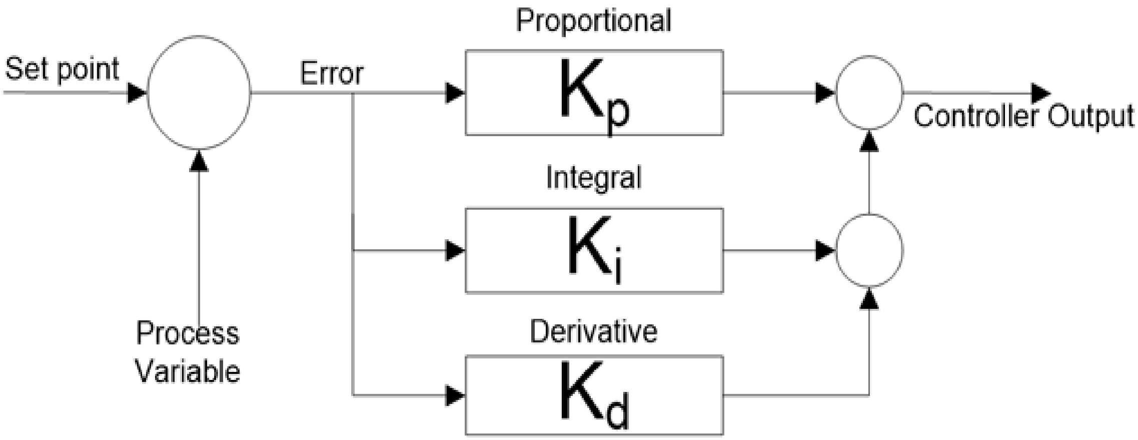

Figure 3. PID block diagram

The proportional term takes into account the current error, which is the difference between the desired set-point and the actual process variable. It then calculates the control output as a proportional response to this error. The proportional term is critical to preventing large deviations from the set-point, but it can itself lead to constant errors and oscillations [2]. This controller has the form

$$f(t) = K_p\, e(t) \qquad (11)$$

K_p – proportional constant.

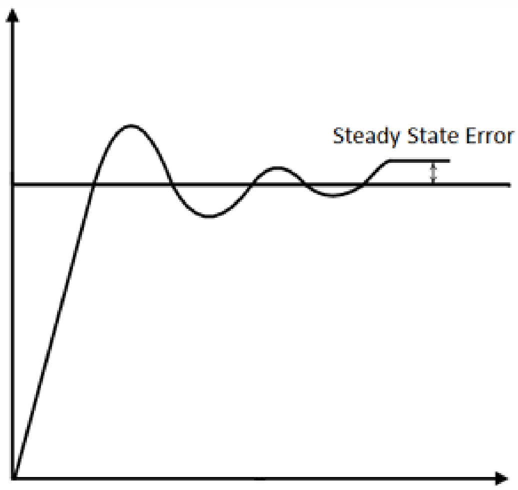

Figure 4. P type controller curve

The integral controller is often used because it can eliminate any bias that may exist. A negative error will cause the signal to enter the system to decrease, while a positive error will cause the signal to increase. The integral controller affects the system by reacting to the accumulated historical error [2]. The format of this controller is as follows:

$$f(t) = K_i \int_0^t e(t) \tag{12}$$

K_i – integral constant.

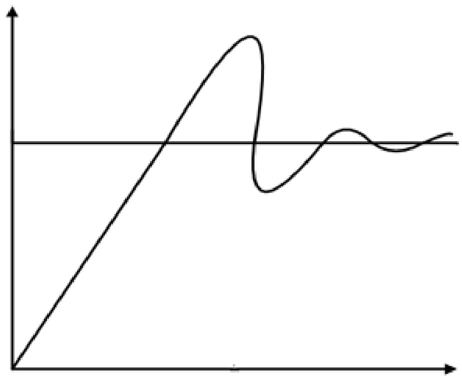

Figure 5. I type controller curve

Derivative control is a form of feedforward control that predicts process conditions by analyzing the change in error. It works to minimize the change in error, thus maintaining constant system settings. The control output is calculated based on the rate of change of error over time [2]. This controller has the form

$$f(t) = K_d \frac{de(t)}{dt} \tag{13}$$

K_d –derivative constant.

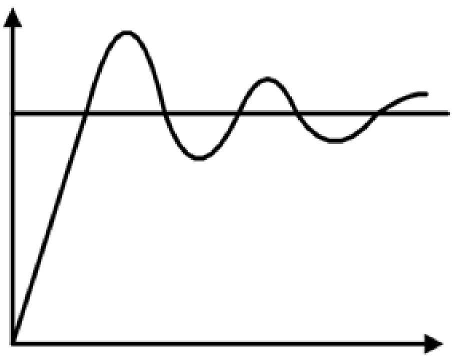

Figure 6. D type controller curve

PID control is the most commonly used because it combines the advantages of each type of control. This includes a quicker response time because of the P-only control, along with decreased zero offset from combined derivative and integral controllers [2]. This controller has the form in equation (14)

$$f(t) = K_p e(t) + K_i \int_0^t e(t) + K_d \frac{de(t)}{dt} \tag{14}$$

For analyzing in PİD controller, equation (14) can be stated as below:

$$f(t) = K_p X + v + K_d \dot{X} \tag{15}$$

$$v = K_i \int_0^t Xd(t), v(0) = 0$$

According to closed-loop system, PID control is demonstrated as below:

$$\Gamma\ddot{X} + \varphi\dot{X} + F_g = K_p X + K_d \dot{X} + v \quad (16)$$
$$v = K_i X$$

In matrix form, the closed-loop system is defined as,

$$\frac{d}{dt}\begin{bmatrix} v \\ X \\ \dot{X} \end{bmatrix} = \begin{bmatrix} K_i X \\ X \\ \Gamma(\varphi\dot{X} + F_g - K_p X + K_d \dot{X} + v \end{bmatrix} \quad (17)$$

For moving the equilibrium to the origin, the following is defined,

$$\check{v} = v - f(0) \quad (18)$$

And, the final closed-loop equation is defined as,

$$\Gamma\ddot{X} + \varphi\dot{X} + F_g = K_p X + K_d \dot{X} + v - f(0) \quad (19)$$
$$v = K_i X$$

To analyze the stability of equations (18), the following properties are necessary:

Property 1. The positive define Γ must satisfy the following condition:

$$0 < \lambda_{\min}(\Gamma) \leq \|\Gamma\| \leq \lambda_{\max}(\Gamma) \leq \tilde{y} \quad (20)$$

$\lambda_{\min}(\Gamma)$ and $\lambda_{\max}(\Gamma)$ are minimum and maximum eigenvalues of matrix Γ, respectively also $\tilde{y}>0$ is taken to be the upper bound [3].

Property 2. f is assumed to be Lipschitz in $\tilde{x}$ and $\tilde{y}$ if

$$\|f(\tilde{x}) - f(\tilde{y})\| \leq \Delta\|\tilde{x} - \tilde{y}\| \quad (21)$$

Since F_g is a continuous function of the first order and satisifies the Lipschitz condition, property 2 is established [3]. The lower bound of $F_g$can be calculated as follows:

$$\int_0^t f dx = \int_0^t F_g dx + \int_0^t d_u dx \quad (22)$$

Taking into account the above analysis of PID control approach is given by the below mentioned theorem:

Theorem. Considering the structural system of equation (10) controlled by PİD control approach of equation (14), the closed system of equations (16) is considered to be asymptotically stable in the equilibrium states of $\left[v - f(0), X, \dot{X}\right]^T = 0$, if the following gains are satisfied [3]:

$$\lambda_{\min}(K_d) \geq \frac{1}{4}\left(\frac{1}{3}\lambda_{\min}(\Gamma)\,\lambda_{\min}\left(K_p\right)^{1/2}\right)\left[1 + \frac{K_e}{\lambda_{max}(\Gamma)}\right] - \lambda_{\min}(\varphi)$$
$$\lambda_{\max}(K_i) \leq \frac{1}{6}\left(\frac{1}{3}\lambda_{\min}(\Gamma)\,\lambda_{\min}\left(K_p\right)^{1/2}\right)\left[\frac{\lambda_{\min}(K_p)}{\lambda_{max}(\Gamma)}\right] \quad (23)$$

The software implemented in this paper is Matlab/Simulink. Simulations are presented to show that the motor vibration can be reduced to a significant level by using a torsional actuator with the developed controllers, thereby validating the effectiveness of the proposed control approach using PID controllers. A simulation period of 20 s is considered for the evaluation [4]. For the simulation purposes, the weight of the torsional actuator is considered to be 5% of the weight of the motor and pump combined. The theorem proposed in this paper provides sufficient conditions for the minimum values of proportional and derivative gains [5]. This theorem confirms that both proportional and derivative gains should be positive since negative gains can make the systems unstable. The PID gains are selected within the stable range using stability analysis to ensure the effectiveness [6].

To compare the results, two blocks of the milling model subsystem were created: one without a control mechanism and one with a control mechanism. Numerical integrators are used to calculate the speed and also provide the acceleration signal. The control signal from the controller subsystem unit is fed to the torsion drive accounting unit to create the required control force. [7].

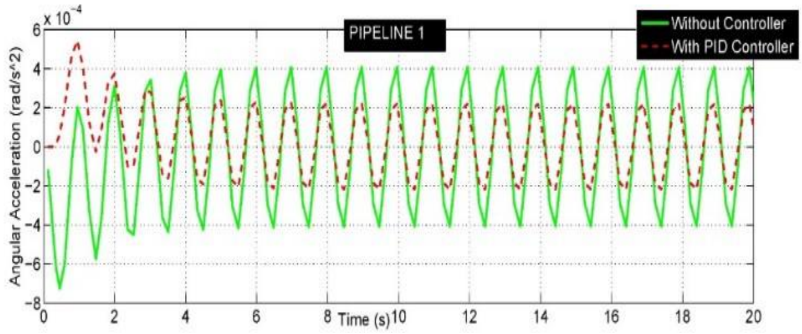

Figure 7. Comparison of motor vibration damping using PID controller for pipeline 1

Figures 7, 8 show the vibration damper of the engine. From these figures, it can be concluded that the PID controller does a good job of minimizing vibration. Figures 9, 10 and are stable, which proves the effectiveness of the PID controller.

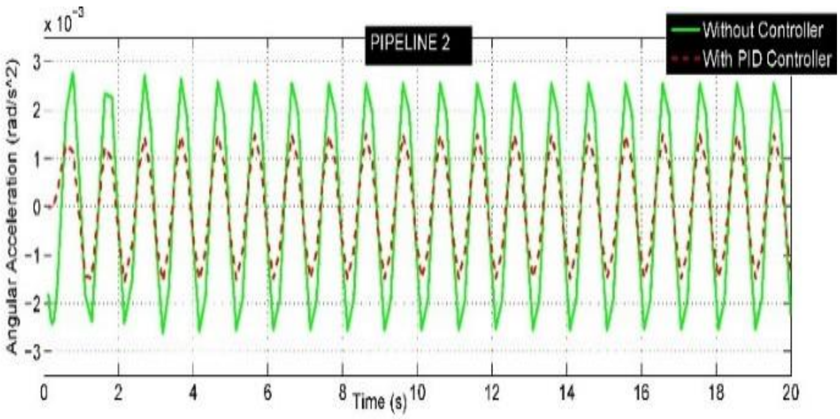

Figure 8. Comparison of motor vibration damping using PID controller for pipeline 2

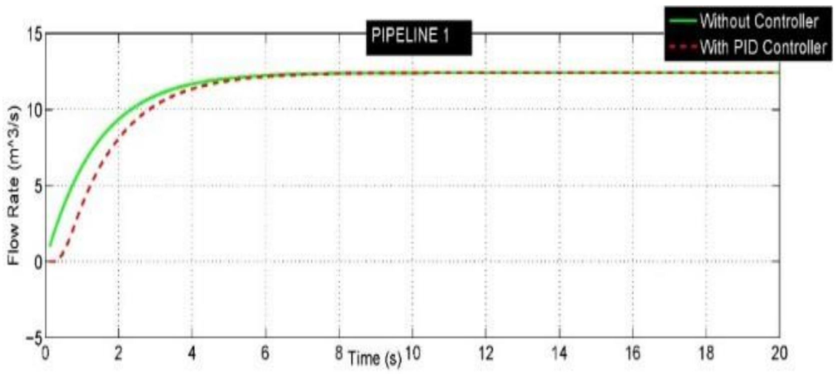

Figure 9. Flow stability using PID controller in pipeline 1

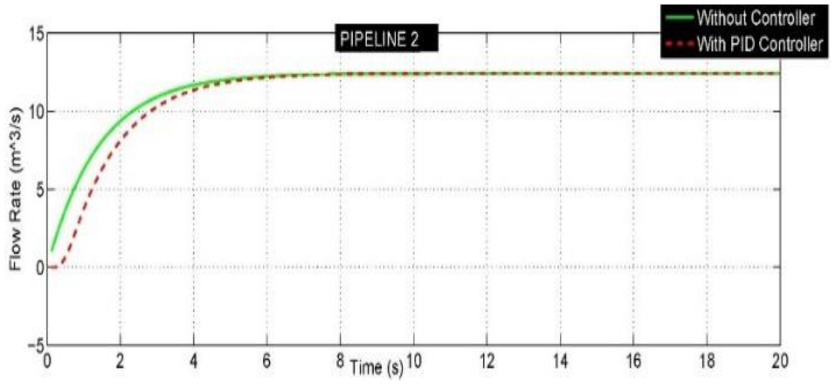

Figure 10. Flow stability using PID controller in pipeline 2

6. Conclusion

In this paper, the necessary conditions for the asymptotic stability of the proposed controller are verified by implementing the Lyapunov stability theorem. The theoretical concepts are verified through numerical simulation and analysis, which proves the effectiveness of the PID controller in pipeline flow control. A new active control strategy is proposed to suppress engine vibration and then control the flow rate of heavy oil pipelines. An important theoretical contribution is made to the stability analysis of the PID controller. The stability conditions necessary for tuning the PID gains are obtained. Sufficient conditions for the proportional, integral and derivative gains are obtained using the Lyapunov stability analysis. The numerical simulation and analysis confirm the effectiveness of the PID controllers in minimizing engine vibration in pipeline flow control. The main points of this paper are:

1. This work confirms the stability of the PID controller which was ignored in previous studies and looks at the flow control.
2. The method of using a torque drive in the construction of a pump-motor is completely new concept.

REFERENCES

1. Thomas A. Huges. Measurement and control basics, 3rd edition, 2002.
2. Rames C. Panda. Introduction to PID controllers-theory, tuning and application to frontier areas, 2012.
3. Sung S.W., Lee J., Lee I-B. Process identification and PID control., IEEE Press, 2009.
4. Basilio J.C. and Matos S.R. Design of PI and PID controllers with transient performance specification. IEEE Transactions on Education, vol. 45, no. 4, pp. 364-370, 2012.
5. Priyanka E.B., Maheswari C., and Meenakshipriya B. Parameter monitoring and control during petrol transportation using PLC based PID controller. Journal of Applied Research and Technology, vol. 14, pp. 125-131, 2016.
6. Q. Xing Li. Design of flow control system based on expert PID. Conference: 2016 International Symposium on Computer, Consumer and Control (IS3C), 2016.
7. Ozkan M., Karakaya B., Turel E., Cicek O., Choban M.T. Linear flow characteristics in control valves. 7th Asia Pacific International Modern Sciences Congress, 2016.

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