Determination of the mass-flow coefficient of jet-reactive turbine’s feed-in nozzle

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Abstract. The possibility of adjusting of the jet-reactive turbine’s head parameters through changing of mass-flow of the working body with the help of adjustable feed-in nozzle is examined. The mass-flow coefficient of the feed-in nozzle is determined experimentally.

1. Introduction

Nowadays, the requirements to the efficiency, environmental friendliness, reliability, and safety of running engines, operating in the national economy, are becoming much more severe. It fully refers to the drives of ball valves of compressor stations (CS) and cross-country pipelines (CCP).

Following the latest demands of the customers the drives of such ball valves should use raw gas (right from the pipe) as the working body and operate the valve under the drive inlet pressure from min 2MPa to maximum pressure (16MPa). Herewith, the drive inlet gas temperature can vary within the range from -60°C till +80°C depending on the ball valve placement and environmental climatic conditions.

For ball valves with flow path diameter DN>300mm the most wide-spread are pneumohydraulic piston-type drives, which are more simple, safer and cheaper than electric motor drives. To provide drive’s operation two kinds of fluids are necessary: raw gas, running right from the gas pipe-line through the control unit to pneumatic cylinder and nonfreezable oil running to the hydraulic cylinder and manual pump. The main disadvantages of such drives are complexity and clunkiness of the construction, low operating efficiency, difficult operation, as constant presence of oil in the system, control over it and its’ refilling (in case of oil leakage emergency conditions appear) are required.

Production of air-powered drives of volumetric operational mode for the required settings of ball valves with big flow-path diameter is quite complicated. It is determined by the necessity of dramatic increase of dimensions of drive’s power section in order to provide the workability of drive under low pressure.

The solving of this problem is possible through the production of the air-powered drive with an engine, making no excess forcing within the whole range of pressures and being safely operated. As such type of engine we offer a simple, relatively cheap, easily reversing turbine’s engine based on the jet-reactive turbine (JRT) [1].

Air-driven drives operating turbine’s air-driven engines are sensitive to the change of the load and are basically suitable for the devices with the stable load and settings of the working body at the inlet. However, in case of necessity, they can be quite easily mechanically adjusted to the computation parameters with the help of regulators of mass-flow, pressure, rotating frequency, etc. It should be noted that while the usage of turbine engine as the air-driven engine there appears the possibility for
the efficiency usage of the great difference of pressures, and taking into account that real pressure in the pipelines is more than 5MPa, turbine engines can compete with the piston ones even according to the coefficient of efficiency).

Figure 1. JRT sketch.

While the usage of turbine-driven engines for the examined series of valves it should also be taken into account that the critical sections of flow section of the turbine-driven engine should have as small dimensions as possible to provide the smallest flow, as energy losses in the supply pipeline are equal to the quadrupled flow. Taking into account all ideas expressed above (possibility for efficiency usage of the great difference of pressures, small dimensions of critical sections) jet-reactive engine and turbine-driven engine, using classical one-nozzle turbines (axial-flow and inward-flow), show themselves up among the series of turbine-driven engines. Jet-reactive engine is easily reversed, has lower flywheel effect and integral pipeline (Figure 1) that decreases the possibility of its freezing, though the coefficient of its efficiency can be lower. The main advantages of the turbine-driven engines comparing to the piston ones is excluding of the emergencies and smaller weight-and-dimensional characteristics.

2. Objectives settings
According to the information stated above it is clearly seen that jet-reactive drives should work with the maximum efficiency or close to it. However, the inlet parameters are not always stable; as a result of this the fast reaction to these changes (regulation) is required. As it has already been mentioned above, the basic methods of JRT parameters regulation is by inlet pressure, rotor spinning frequency, and mass-flow. The last method we shall study in details, as the change of mass-flow can be achieved without any additional expenditures and complication of the drive’s construction.

3. Aim of research JRT
The aim of the work is to receive experimental dependences of the mass-flow and the flow coefficient of feed-in nozzle depending on the JRT inlet pressure, what, being based on these dependences, will allow in future using the feed-in nozzle even as the flow-meter.

As the first stage of researches in Sumy State University (Technical Thermophysics Department) there was made a test stand for the researching of the jet-reactive turbines and based on them pneumatic units, for the improving of the calculation methodology of JRT characteristics and receiving basic nondimensional dependences.

The model of the jet-reactive turbine as the basic element of the test stand is presented in Figure 2.
Jet-reactive turbine is a machine of the dynamic action principle. The main elements of jet-reactive turbine are flow-in (feed-in) nozzle (FN) and rotor, consisting of the hollow shaft with the radial pipes cantilevered on it. At the end of the pipes there are hauling nozzles (HN) placed in tangentially.

Gas is running through the feed-in nozzle to the hollow rotor shaft and further through the gas path to the HN. In the feed-in nozzle the potential energy of compressed gas is transformed into the kinetic energy releasing together with sonic and supersonic speed of gas flow, which in its turn creates jet reaction and as a consequence rotation moment on the turbine shaft, which in its turn is calculated according to the famous dependence [2]:

\[ M_r = M_U - M_{r.r} = M_U - K_{r.r} \omega_r^2 \]  

(1)

in which: \( M_U \) – moment, which is defined according to the theorem of moment of momentum of the gas flow relatively to the spinning axis, based on the co-operation of gas flow with JRT flow part; \( M_{r.r} \) – rotor resistance moment in the environment (aerodynamic moment); \( K_{r.r} \) – aerodynamic resistance coefficient; depends on density of the environment, rotor outside diameter, shape, quantity and mutual position of pipes of shoulder tubes of rotor; rotation frequency of the turbine shaft; it can be defined only experimentally; \( \omega_r \) - angular rate of turbine rotation.

For the no-load conditions, when \( M_r = 0 \), we shall receive (not taking into account mechanical losses in bearings)

\[ M_U = M_{r.r} = K_{r.r} \omega_r^2 \]  

(2)

Moment \( M_U \) is equal [3]:

\[ M_U = R_w \frac{D}{2} - G_r \omega_r \frac{D^2}{4} \]  

(3)
where: $R_w$ - tractive force of hauling nozzles in relative motion; $D$ – diameter of the axes position of hauling nozzles relatively to the axis of spinning; $G_r$ – gas flow through the hauling nozzles; $\omega_{nl}$ – angular rate of spinning of JRT rotor in the non-load mode.

Then

$$K_{rr} = \frac{M_f}{\omega_{nl}} = \frac{R_w D}{2} - G_r \omega_{nl} D^2 \omega_{nl}$$

(4)

Application programs, which allow calculation of the JRT characteristics taking into account this coefficient are worked out: dependencies are the following $M_f = f(n)$; $N_r = f(n)$; $\eta_r = f(n)$ both, under $K_{rr} = const$ and under approximate dependence $K_{rr} = f(n)$.

Power on the turbine shaft and efficiency coefficient is calculated according to the formulas:

$$N_r = M_f \omega_r \quad \text{and} \quad \eta_r = \frac{N_r}{G_s h_s}$$

(5)

where: $G_s$ – gas flow through the JRT feed-in nozzles; $h_s$ – isentropic work of 1 kg expansion of the working body from the stagnation parameters at the JRT inlet to the environmental pressure.

For the calculation of the head parameters and characteristics of JRT and pneumatic units, based on it, it is necessary to know actual gas flow through feed-in nozzle and that is the coefficient of this nozzle flow. Besides, the receiving of experimental dependencies of mass-flow and coefficient of feed-in nozzle flow, depending on the pressure on the JRT inlet will allow in future using the feed-in nozzle also as a flow-meter. That is why the experimental researches on the determination of the coefficient of feed-in nozzle flow in different positions of valve needle and pressures at the inlet were conducted. (see Figure 3)

![Figure 3. Feed-in nozzle structure (FN).](image)

In its structure feed-in nozzle consists of: supply pipe with pressure gage placed on it for inlet pressure measurements; casting, in which needle seat with expansion angle 60º, constructing outer nozzle closure, is placed; regulation needle, spinning along the thread of screw in the casting and having possibility to move in the axial direction tightening to the seat. Thus, nozzle flow path is reduced. Pith of metric screw thread in the casting for the needle is equal 1mm.

Position, in which, the needle was completely tightened to the seat (nozzle fully closed) was considered to be the starting mode. For this needle position $h=0$ mm (see Figure 3). Then, needle was gradually moving back to $h=16$.

For the conduction of measurements and obtaining basic gas-dynamic dependencies there was constructed the test stand, structural drawing of which, is presented in Figure 4. The test stand allows examining starting and no-load modes of jet-reactive turbine.
Figure 4. Structural drawing of the experimental unit.

The figure shows: F – air-intake filter; C – compressor; V – shut-off valve; EV – emergency valve; R – receiver; RV – regulation valve, G₁, G₂ – pressure gages; PV – pressure-control valve of vessel-type; T₁, T₂ – temperature meters (electronic multi-meter); AR – air-flow regulator (feed-in unit of JREM); LG – load gage of weight type; JREM – jet-reactive expansion machine; T – tachometer; FM – flow-meter; DG – differential pressure gages.

Figure 5 shows the results of the measurements. As it is seen from the graphical curves, while the increasing of the needle move h>10 mm lines \( m = f (p) \) overlap each other and that is the proof of the full opening of the nozzle section, if \( h = 10 \text{ mm} \). This conclusion is traced better in the diagram of dependence \( m = f (h) \), presented for some values of pressure in Figure 6.

Figure 5. – Dependence of mass-flow from inlet pressure in the feed-in nozzle.

Diagrams character proves theoretical dependencies of the gas flow through the nozzle and the nozzle head [4]. Gas mass-flow while the process of isentropic flow through the short nozzle head from the hollow of unlimited volume is described by two equalizations:

- for the pre-critical mode suits the equalization:
\[ G_{ns} = f_{\min} P_{in} \sqrt{\frac{2k}{RT_{in}(k-1)}} \left[ \left( \frac{p_{out}}{p_{in}} \right)^{\frac{k}{k+1}} - \left( \frac{p_{out}}{p_{in}} \right)^{\frac{k+1}{k}} \right], \quad \frac{p_{out}}{p_{in}} \geq \beta_{cr} \] (6)

- for the post-critical mode suits the equalization:

\[ G_{ns} = f_{\min} P_{in} \sqrt{\frac{k}{RT_{in}(k+1)}} \left( \frac{2}{k} \right)^{\frac{k+1}{k-1}}, \quad \frac{p_{out}}{p_{in}} \leq \beta_{cr} \] (7)

in which, \( f_{\min} \) - minimal flow area for the feed-in nozzle.

Figure 6. – Dependence of mass-flow from the needle move for different pressures in the nozzle inlet.

Because of the existence of the of the intake center body (needle) of complicated shape and cone-type surface of nozzle seat, under the low values of needle move \( h \) (needle is placed in the critical cross-section) gas flows through the axisymmetric cone-type gap. In this case, the minimal side surface area of the truncated cone must be considered to be the area of the flow-path nozzle (Figure 7 (a)). For the fully opened nozzle the area of the flow-path is determined by the area of critical size of the flow-path with the diameter \( d_{cr,f} \) (Figure 7 (b)).

Figure 7. Calculation of the area of the flow path of the feed-in nozzle: (a) for low values of needle move; (b) for fully opened nozzle.
For the correct calculation of the area of the flow path of nozzle of determined geometry there is created a computer program, which calculates the minimal value of the area $f_{\text{min}}$ for any intake center body position (Figure 8).

![Diagram of $f_{\text{min}}$ vs. h, mm]

**Figure 8.** Dependence of the $f_{\text{min}}$ on the needle move.

The true process of gas flow from the nozzle is calculated by the flow coefficient $\mu = \frac{G_g}{G_{\text{in}}}$, equal to ratio of actual gas flow through the nozzle to the theoretical one.

After determination of actual air flow through the feed-in nozzle it was necessary to find the value of flow coefficient for this nozzle. For each experimentally obtained value of gas flow according to the needle move and inlet pressure in the JRT it was distinguished the correspondent theoretical value, and consequently the flow coefficient.

In the result the graphical diagram of changes $\mu = f(h)$ was received. It is presented in Figure 9.

![Diagram of $\mu$ vs. h, mm]

**Figure 9.** Ratio of flow coefficient of feed-in nozzle and needle move.

In the diagram it is clearly seen that under quite low values of the needle move ($h = 0 \div 2 \text{ mm}$), flow coefficient has relatively low value and is dependent on $h$, that is conditioned by the construction specifications of the feed-in nozzle (huge losses while the gas flow through the “narrow” gap between the needle and the seat exist). For other needle positions the coefficient $\mu$ becomes constant, close to
0.9 (Figure 10). Then, this value is input into the program for the calculation of head settings and characteristics of jet-reactive expansion machine and unit in general.

![Figure 10. Dependence of flow coefficient on the inlet pressure for the needle move value $h \geq 2\, mm$.](image)

4. Conclusions
Experimental dependences of mass flow and flow coefficient for the regulating feed-in nozzle of jet-reactive turbine in different positions of regulating needle and with different pressure values in the nozzle inlet were received, that allowed clarifying of techniques for calculation of turbine head settings and characteristics.

It was defined that while the needle move from the stop mode into the casting $h \geq 2\, mm$ flow coefficient of feed-in nozzle remains actually constant and equal to 0.9.

Obtained dependencies also allow refusing from installing flow-meters, and defining actual gas flow right by the diagram for jet-reactive turbines with similar construction of supply nozzle.

References
[1] Vanyeyev S M, Korolev S K, Rukhlov Y L, Fedotov Y T 1990 Jet-reactive engine and possibilities of its usage Chemical and Oil Engineering 6 pp 16-17
[2] Vanyeyev S M 1999 Calculation of jet-reactive turbine characteristics Reporter of “KPI”: Mashinostroenie 36 pp 263-269
[3] Vanyeyev S, Berezhnoi A 2012 Influence of gap between driving wheel and corps on characteristics of jet-reactive turbine Procedia Engineering 39 pp 1-8
[4] Abramovich G N 1991 Applied gas dynamics / 5-th edition, overworked and extended (M: Nauka) pp 600