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ИСПОЛЬЗОВАНИЯ ГАЗОВЫХ ПОТОКОВ В СТРОЙНЫХ АППАРАТАХ В ПРОЦЕССЕ СЕПАРАЦИИ

APPLICATION OF GAS FLOWS IN JET DEVICES FOR GAS SEPARATION

Новрузова Судаба
кандидат технических наук,
доцент кафедры нефтегазовая инженрия,
Азербайджанский государственный университет
нефти и промышленности
sudaba.novruzova@mail.ru

Гадашова Эльмира
кандидат технических наук,
ассистент кафедры нефтегазовая инженрия,
Азербайджанский государственный университет
нефти и промышленности
elmira_qadashova@hotmail.com

Алиев Инглаб Намиг
кандидат технических наук,
доцент кафедры нефтегазовая инженрия,
Азербайджанский государственный университет
нефти и промышленности
inqilab.aliyev@hotmail.com

Novruzova S.G.
PhD, Associate Professor,
Department of Oil and Gas Engineering,
Azerbaijan State Oil and Industry University
sudaba.novruzova@mail.ru

Gadashova E.V.
PhD, Assistant,
Department of Oil and Gas Engineering,
Azerbaijan State Oil and Industry University
elmira_qadashova@hotmail.com

Aliyev I.N.
PhD, Associate Professor,
Department of Oil and Gas Engineering,
Azerbaijan State Oil and Industry University
inqilab.aliyev@hotmail.com

Аннотация. В данной статье рассматривается и обсуждается проблема достижения низких статических температур газовых потоков при адиабатическом расширении газа в сравнении с дросселированием газовых потоков при резком градиенте давления, как, например, при снижении давления до 10 МПа в условиях низких температур – температурные газовые сепараторы (ГС) и обсуждаются результаты расчетов, полученные при трех различных режимах течения газа: трансзвуковом, звуковом и сверхзвуковом режимах течения газа с числом Маха более 0,6. Так как ситуации адиабатического расширения газа из-за резкого неожиданного перепада давления возникают в промышленности достаточно часто, особенно на сужающихся участках газотранспортной системы, и наносят существенный ущерб и прямой вред в виде образования сосулек и гидратов, которые впоследствии еще больше сужают поток через сужающие сопла и подобное оборудование эффективно блокирует его. Вместе с тем такие повреждения потенциально могут представлять коррозионную опасность с последующим выходом оборудования из строя. Это особенно актуально при разделении и транспортировке газов. Кроме того, такое движение вызывает значительные изменения скорости звука, регистрируемые вокруг сужающих сопел, задвижек, регулирующих клапанов и других подобных устройств. Полученные в расчетах результаты, которые практически невозможно получить эмпирически, и основные параметры характерны для типовых режимов работы струйных аппаратов, используемых в газосепараторах, при достижении низкостатических температур.

Ключевые слова: адиабатическое расширение, адиабатическое охлаждение, течение газа, сепарация.

Annotation. In this article we consider and discuss a problem of achieving low-static temperatures of gas flows in adiabatic expansion of gas versus throttling of gas flows in case of a sudden pressure gradient, like, for example, during pressure reduction to 10 MPa in the low-temperature gas separators (LTS) and discuss calculation results obtained at three different gas flow regimes: transonic, sonic, and supersonic gas flow regimes with Mach number higher than 0.6. As situations of adiabatic expansion of gas due to a sudden unexpected pressure drop occur rather often in the industry, especially in narrowing parts of the gas transport system and cause significant deficiencies and outright harm in form of formation of icicles and hydrates, which subsequently further narrow the flow through the narrowing nozzles and similar equipment effectively blocking it. Alongside with that such damage can potentially pose corrosion hazard with subsequent failure of the equipment. This is especially relevant during gas separation and transporting. Furthermore, such motion causes significant alterations to the speed of sound registered around the narrowing nozzles, latches, control valves and such other devices. The results obtained in the calculations, that are nigh to impossible to obtain empirically, and basic parameters are representative of typical work modes of jet apparatuses used in gas separators when achieving low-static temperatures.

Keywords: adiabatic expansion, adiabatic cooling, gas flow, separation.

1. Introduction. It is a common knowledge, that it is impossible to ensure high-quality gas preparation for transport using only conventional throttle method with natural cool during gas flows'

pressure reduction to 10 MPa in the low-temperature gas separators (LTS). Artificial cooling in the ammonia or propane refrigerators is required, which is not always economically viable.

In this scenario use of low-static temperature high-velocity flows during their adiabatic expansion is considered. Such a temperature in the technical literature on aerodynamics is referred as: true, thermodynamic, static or local gas flow temperature (Leontovich M., 1983; Baker et al, 2008).

2. Experimental part. Low-static temperatures generated at transonic and supersonic speeds of gas flows with Mach number > 0.6, and with increase in this number (i.e. velocity of the gas flow) even static temperatures cannot be measured directly, since such a measurement requires motion of the measuring device at the same high speed as the gas flow. Achieving such a motion is nigh impossible. This temperature of the high-speed flows can be determined analytically through gas flow deceleration temperature, i.e. mentally imagined stopped gas flow (W = 0). After gas separation in the environment of low-static temperatures, their values can be determined through gas wetness degree (i.e., through dew point temperature) of the separated gas flow (Panahov R.A. et al., 2014; Carta et al., 2013; Althuluth et al., 2014).

Creation of low-static temperatures can be observed in various hydrodynamic processes, in high-velocity flows' efflux in shot time spans and in limited volume. This phenomenon is considered negative both in aviation and in natural gas industry, methods of its prevention and elimination are being constantly developed.

Laws of aerodynamics imply, that in certain regions of flow around convex surfaces outside the border layer the flow velocity is higher, than in oncoming flow. Hence, in these regions temperature is lower than in oncoming flow.

This situation is observed in the narrowing parts of a gas transport system (gauges, valves, latches, control devices). During separator evacuation through semi-open latches these fixtures can behave as narrowing nozzle or Laval nozzle. After liquid has been extracted from the separator and brief efflux of gas through these latches into the atmosphere, gas flow may acquire transonic or supersonic velocity. As a result, walls of the latches and discharge tube can cool below 0 ºC due to low-static temperatures effect which would lead to condensation and subsequent freezing of the atmospheric moisture. This process can result in formation of hydrate-ice plugs in the said places. Such a negative impact may incapacitate latches and control device valves of a gas transport system.

Snow deposits in parts of the tube directly adjacent after the latches is a common occurrence during even small pressure changes in the gas flow. An attempt to explain this as a common gas throttling event (Joule-Thompson effect) is incorrect, as pressure change in the flow is insufficient to cause gas cooling as a result of Joule-Thompson effect. Adiabatic expansion of the high-velocity gas flow with local low-static temperatures of the said flow is a more likely culprit. In these cases, moisture freeze, and hydrate crystals formation can often partially plug though holes of narrowing nozzles thus, causing an equipment failure. Moisture freeze and ice formation in high-speed gas flows can be experimentally observed, as water is introduced into the effusing flow. Special measures are undertaken to mitigate this issue in gas transport systems, same to the aviation industry.

3. Results and discussion

Results of the low-static temperatures acquisition in adiabatic expansion of gases at initial pressure of P_o = 10 MPa and initial temperature of t_o = 20 ºC depending on the initial and terminal pressures and based on gas-dynamic relations are given in the table below. Here values of the static pressure (P_{st} = P_{sep}), the pressure changes $\Delta P = P_o - P_{st}$ and temperature changes $\Delta t = t_o - t_{st}$, Mach number and velocities of the gas flow depending on the acquired low-static temperatures are demonstrated.

Results are calculated for transonic, sonic, and supersonic flow regimes.

Table 1 – Comparison of the calculational parameters during adiabatic expansion and throttling of gases. Source: Composed by the authors

Adiabatic expansion of gases								
Transonic regine				Sonic (critical regime)	Supersonic regime			
P_o/P_{st}	1,356	1,471	1,737	1,83	1,90	2	2,5	3
P_{st}, MPa	7,37	6,80	5,76	5,46	5,26	5,0	4,0	3,33
$\Delta P = P_o - P_{st}$, MPa	7,63	3,20	4,24	4,54	4,74	5,0	6,0	6,67
t_{st}, ºC	0	–5	–15	–18	–20,4	–23,2	–35,7	–45
$\Delta t = t - t_{st}$, ºC	20	25	35	38	40,4	43,2	55,7	65
M	0,672	0,787	0,950	1	1,03	1,07	1,25	1,38
W, m/s	299	333	396	414	425	440	500	544
Gases throttling								
P_k, МПа	7,37	6,8	5,76	5,46	5,76	5,0	4,0	3,33
$\Delta P = P_H - P_k$, MPa	2,63	3,2	4,24	4,54	4,74	5,0	6,0	6,67
t_{fin}, ºC	10,8	8,8	5,2	4,1	3,4	2,5	–1	–3,3
$\Delta t = t_H - t_k$, ºC	9,2	11,2	14,8	15,9	16,6	17,5	21	23,3

The respective values for cooling of gas due to throttling process in the same initial parameters are provided in order to demonstrate superiority of adiabatic expansion method over gas throttling. Table data and gas-dynamic relations analysis clearly shows that:

– to achieve static temperature: $t_{st} = 0$ in the observed precritical environment and at initial parameters of: $P_o = 10$ MPa and $t_0 = 20$ ºC value of $P_o/P_{st} = 1{,}356$ is sufficient, i.e. pressure change of 2,63 MPa, but during gas throttling process in the same initial conditions, is just $t_{fin} = 10{,}8$ ºC. Wherein in adiabatic expansion process coefficient α_S – is equal to: $\alpha_S = \Delta t/\Delta P = 20/2{,}63 = 7{,}6$ ºC/MPa, though in throttling process: $\alpha_i = 10{,}8/2{,}63 = 3{,}49$ ºC/MPa, 2,18 times less ($\alpha_S/\alpha_i = 7{,}6/3{,}49 \approx 2{,}18$); – at the critical gas flow regime, in the observed initial conditions ($P_o = 10$ MPa и $t_0 = 20$ ºC), low-static temperature reaches negative 18 ºC in an adiabatic expansion process, while in a throttling process final temperature only reaches 4,1 ºC. In this regime α_S/α_i ratio becomes 8,37/3,5 = 2,39, i.e. α_S/α_i increases with increments in Mach number or velocity of the gas flow: – in supersonic flow regime (M = 1,38) in the aforementioned initial conditions low-static temperature reaches negative 45 ºC if pressure ratio is $P_o/P_{st} = 3$ or pressure change is $\Delta P = 6{,}67$ MPa; in this case pressure drop equals: $\Delta t = 65$ ºC and $\alpha_S = 65/6{,}67 = 9{,}74$, wherein during throttling process $t_k = -3{,}3$ ºC, $P_k = 3{,}33$ MPa, $\Delta P = 6{,}67$ MPa, $\Delta t = 23{,}3$ ºC, $\alpha_i = 23{,}3/6{,}67 = 3{,}49$. In this regime ratio equals: $\alpha_S/\alpha_i = 9{,}74/3{,}49 = 2{,}79$. Consequently, static temperature is significantly lower in adiabatic expansion of gases with increments in gas flow velocity, than final temperature is in gas throttling process $t_{st} << t_k$.

Aerodynamic curves analysis for adiabatic expansion of gas flows for 3 (transonic, sonic, and supersonic) regimes demonstrate (Aliyev et al., 2007; Mustafayev et al., 2015; Yeyamtsev, 1983) – as initial conditions are lowered (P_o, t_o) all three regimes require smaller pressure changes to achieve low-static temperatures;

– to get $t_{st} = 0$ ºC at the atmospheric pressure $P_{st} = 0{,}1$ MPa, in an adiabatic expansion process with initial temperature 20 ºC, initial pressure would be: $T_o/T_{ст} = 293/273 = (P_o/0{,}1)0{,}23$; $1{,}0734{,}33 = P_o/0{,}1$; $P_o = 0{,}1 \cdot 1{,}357 \approx 0{,}14$ MPa. That is to say that to get tst = 0 in the atmospheric conditions it only suffices to have a pressure drop of $\Delta P = 0{,}14 - 0{,}1 = 0{,}04$ MPa. Such an insignificant pressure drop leads as mentioned above to formation of snow deposits on the surface of purge valves of a separator;

– characteristic element of a transonic regime (M < 1) is that with decrease in the cross-sectional area of the narrowing nozzle (dT < 0) flow velocity increases (dW > 0). Wherein nozzle flow pressure, density, temperature of the gas decrease, local speed of sound decreases as well (pic. 1);

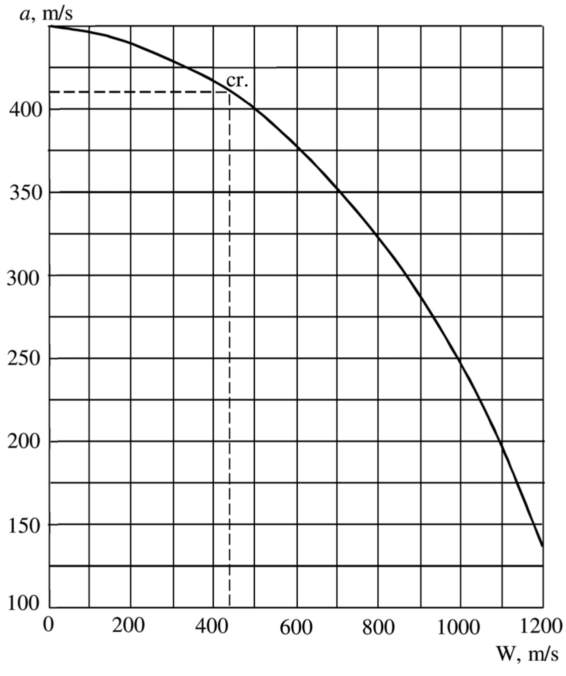

Figure 1 – Correlation between gas flow velocity and speed of sound. Source: Composed by the authors

– critical flow regime is a special case situated at the limit between transonic and supersonic flows. It is commonly known that as pressure drop increases (or Po/P ration) nozzle velocity increases as well, and speed of sound in such a flow decreases. Finally, at a certain pressure drop flow velocity (W) and local speed of sound (a) come to an equilibrium ($W = a = W_{cr}$ = acr; M = 1) marking start of a critical flow regime; – in adiabatic flow critical velocity can be reached in the narrowest cross-section of the tube or in the end of a narrowing nozzle. In this critical cross-section critical velocity and critical (maximal) flux are established «automatically»;

– gas flow velocity is independent of the absolute value of the initial pressure (P_o at $W \approx 0$) nor it depends on the pressure drop ($\Delta P = P_o - P$), it depends on initial deceleration velocity (T_o at $W \approx 0$) and pressure ratio (P/P_o) under effect of which the effluxes occur;

– the lower the P/Po ratio, the higher flow velocity; yet even as pressure ratio approaches zero $P/P_o = 0$ (which can occur if the efflux happens in an absolute vacuum or if initial pressure approaches infinity $P_o = \infty$) velocity cannot increase infinitely. Theoretically maximal velocity is independent of the initial deceleration pressure (P_o) and is defined by physical properties of the gas (through values of K and R) and value of the initial deceleration temperature (T_o):

$$W = \sqrt{\frac{2k}{k-1} gRT_o}_{max}.$$

For the natural gas (methane) at t_o = 20 ºC: $W_{max} = 67{,}06\sqrt{T_o} = M\,47$ m/s.

4. Conclusions. It is important to understand that in all gas flow regimes constant values of the critical parameters and resting gas parameters, maximal velocity ($P_{cr.}$, $\rho_{cr.}$, $T_{cr.}$, P_o, ρ_o, T_o), as well as non-dimensional parameters: Mach number ($M = W/a$) velocity coefficient ($\lambda = W/a_{cr.}$) are ground parameters in determination of low-static temperature of a gas flow;

– speed of sound (or speed of propagation of small perturbations), that is defined by formula: $a = \sqrt{kgRT}$, only depends on molecular structure of a gas and its temperature, yet is completely independent of motion conditions;

– speed of sound dependence (a) on the gas flow velocity is only a result of gas temperature change; thus, as the velocity of an adiabatically expanding flow increases (i.e. as temperature decreases) the speed of sound decreases as well, and as such velocity decreases (i.e. temperature increases) so does the speed of sound increase.

– gas flow critical velocity ($W_{cr} = a_{cr}$) is a criterion for flow regimes, meaning that at $W < W_{cr}$ – the flow is subcritical, at $W > W_{cr}$ – supercritical; – gas flow critical parameters (W_{cr}, P_{cr}, ρ_{cr}, T_{cr}), as well as deceleration parameters (P_o, ρ_o, T_o) at $W = 0$, are constant and remain constant for the entire isentropic flow.

Thus, gas flow critical regime at which gas flux becomes maximal is, in general, a calculable regime for all jet apparatuses. Constant parameters of this regime greatly simplify aerodynamic calculations, including low-static temperature values determination, that practically cannot be measured directly.

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