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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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Wet Steam Discharge Coefficient of a Standard Nozzle and Orifice Plate

List of symbols

- c – friction coefficient,
- F – cross-section [m^2],
- G – flow rate [kgs^{-1}],
- p, P – pressure [bar, Nm^{-2}],
- Re – Reynolds number,
- v – specific volume [m^3kg^{-1}],
- x – relative dryness,
- α – discharge coefficient,
- α^* – volume concentration coefficient,
- ε – expansion coefficient,
- κ – isentropic exponent,
- μ – contraction coefficient, viscosity [–, $kgs^{-1}m^{-1}$],
- ρ – specific mass [$kg\,m^{-3}$].

Subscripts

- f – liquid phase,
- F – friction,
- g – vapor phase,
- tp – two-pase fluid,
- κ – with compressibility,
- 1 – before the throttling device,
- 2 – behind the throttling device.

The development of the nuclear plants has been followed by an extensive application of the wet steam as a working medium. The demand for the wet steam flow rate measurements has increased accordingly.

A direct use of the data included in the Standards [6] for measuring the flow rate is impossible. The papers [1÷5] deal mainly with the problems of measuring the flow rate of the wet steam by means of throttling devices. The theoretical approach adopted by authors of the afore-mentioned papers makes their solutions applicable in different ranges of the values of x and p.

Experimental verification of the above methods has been performed mostly under considerably high pressures and for low values of the relative dryness.

The wet steam parameters in the secondary system of the nuclear power plants with pressurized water reactors may be characterized by the pressure $p = 0.05 \div 50.0$ bar and the relative dryness $x > 0.8$. Let us characterize this range of the parameter values by introdu-

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cing the volume concentration coefficient α^* given by the relation

$$\frac{1-\alpha^*}{\alpha^*}=\frac{w_f}{w_g}\frac{v_f}{v_g}\frac{1-x}{x}. \tag{1}$$

With the standard arrangement and for the usual diameters and droplets concentrations we can assume that the velocity of the both phases equals when the wet steam flows through the installation of the recommended design. The values of α^* calculated under this assumption are given in Table 1.

Table 1

Volume concentration coefficient α^* calculated for the identical velocities of the both phases as a function of the pressure p and the relative dryness x

	α^*				
p \ x	0.9	0.8	0.5	0.2	0.1
0.05 bar	0.999996	0.999991	0.999964	0.99986	0.99968
0.5	0.999966	0.999923	0.99969	0.9988	0.9972
5.0	0.99968	0.99927	0.9971	0.9885	0.9745
50.0	0.9964	0.9920	0.9686	0.8851	0.7739

The high values of coefficient α^* indicate the possibility of using a homogeneous model for solving the flow in the throttling devices.

It is necessary, however, to accept an exigence that the pressure drop in the throttling device should be small so as to prevent considerable phase changes in the throttling device. These changes can not be considered in the frame of the homogeneous model of the flow.

Assumptions and basic equations

In a homogeneous model it is assumed that the two-phase mixture can be regarded as a continuum with physical properties ascribed by its composition. The forthcoming investigations will therefore concern the influence of the mixture composition upon the values of physical parameters characterizing the flow of the mixture through the throttling device. We maintain formally the basic equations given in [6] for calculating the flow rate measured by the throttling device. So we need to measure only the same parameters as for flow rate measurements of one-phase fluid.

The basic equations have the following form:

$$G=\alpha\varepsilon F\sqrt{2(P_1-P_2)}\sqrt{\rho}, \tag{2}$$

$$\alpha=\frac{\zeta\mu}{\sqrt{1-\mu^2m^2}},\quad m=\left(\frac{d}{D}\right)^2, \tag{3}$$

$$\alpha_\kappa = \frac{\zeta \mu_\kappa}{\sqrt{1-\mu_\kappa^2 m^2}}, \tag{4}$$

$$\varepsilon = \frac{\alpha_\kappa}{\alpha} \sqrt{\frac{1-\mu_\kappa^2 m^2}{1-\mu_\kappa^2 m^2 \left(\frac{P_2}{P_1}\right)^{\frac{2}{\kappa}}}} \sqrt{\frac{1}{1-\frac{P_2}{P_1}} \frac{\kappa}{\kappa-1} \left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\kappa}} - \left(\frac{P_2}{P_1}\right)^{\frac{\kappa+1}{\kappa}}\right]}. \tag{5}$$

The homogeneous model does not include the inter-phase effects and, therefore, is restricted to the cases of small pressure differences $P_1 - P_2$ limited by the inequality $(P_1-P_2)/P_1 \leqslant 0.2$. The contraction coefficient for a nozzle is defined according to [6] as

$$\mu = \mu_\kappa = 1. \tag{6}$$

For an orifice plates – according to Buckingham [7] – we have

$$\mu = 0.578 + 0.395\ \mathrm{m}^2. \tag{7}$$

The limitation: $(P_1-P_2)/P_1 \leqslant 0.2$ enables us to assume that

$$\mu_\kappa \doteq \mu. \tag{8}$$

It can be easily seen that the assumptions (7) and (8) are followed by a relation

$$\alpha \doteq \alpha_\kappa. \tag{9}$$

Expansion coefficient ε

The equation of state $p \cdot v^\kappa = \text{const}$ describing an isentropic expansion is the basis for the derivation of the equation (5). This equation is not correct, from the thermodynamic point of view, for the description of the isentropic processes in the wet steam.

The experience has shown nevertheless that this equation gives numerical values sufficiently accurate for small values of the pressure differences. In order to preserve the same system of equations both for the one-phase fluid and the wet steam, we may use – with sufficient accuracy – the κ values given in [8].

Discharge coefficient α

To derive the discharge coefficient α we shall assume that the pressure ratio on the throttling device $P_1/P_2 \to 1$. Then equation (2) can be simplified to the following form

$$G = \alpha F \sqrt{2(P_1-P_2)}\sqrt{\rho}. \tag{10}$$

The values of the discharge coefficient α given in the Standards [6] are valid for the standard pressure corner taps P_1, P_2. In forthcoming investigations the values of static pressures P_1', P_2' appearing in the equation (10) will be needed. For a nozzle we assume [6] $\mu = 1$; therefore P_2' will correspond to the pressure in the nozzle outlet cross-section. For the orifice plate we put $P_2'=P_2$. Standing upon the data presented in [6] we express P_1' and P_2' by means of the following relations

$$P_1'=P_1+\beta_1(P_1-P_2), \tag{11a}$$

$$P_2'=P_2+\beta_2(P_1-P_2), \tag{11b}$$

where

$$\beta_1=\beta_1(m), \tag{12a}$$

$$\beta_2=\beta_2(m). \tag{12b}$$

The values of β_1 and β_2 for the orifice plate and the nozzle are plotted in Figs. 1 and 2 in an agreement with the data derived from [6]. In the course of the forthcoming calculations the functions $\beta_1=\beta_1(m)$ and $\beta_2=\beta_2(m)$ for a nozzle are being approximated by the following relations

$$\left.\begin{array}{ll} \beta_1=0.0 & \text{or } m<0.05 \\ \beta_1=-0.61(m-0.05)^2 & 0.05<m<0.35 \\ \beta_1=-0.367(m-0.2) & 0.35>m \\ \beta_2=0.005 & \text{for all } m \end{array}\right\} \tag{13a}$$

For the orifice plate there is analogously

$$\left.\begin{array}{ll} \beta_1=0.0 & \text{for } m<0.2 \\ \beta_1=-0.615(m-0.2)^2 & 0.2<m<0.5 \\ \beta_1=-0.3715(m-0.35) & m>0.5 \\ \beta_2=0.0 & \text{for all } m \end{array}\right\} \tag{13b}$$

The equation (10) can be rewritten in the following form

$$G=\frac{1}{\sqrt{1+\beta_1-\beta_2}}\,\alpha F\sqrt{2\rho_{tp}}\sqrt{P_1'-P_2'}\,. \tag{14}$$

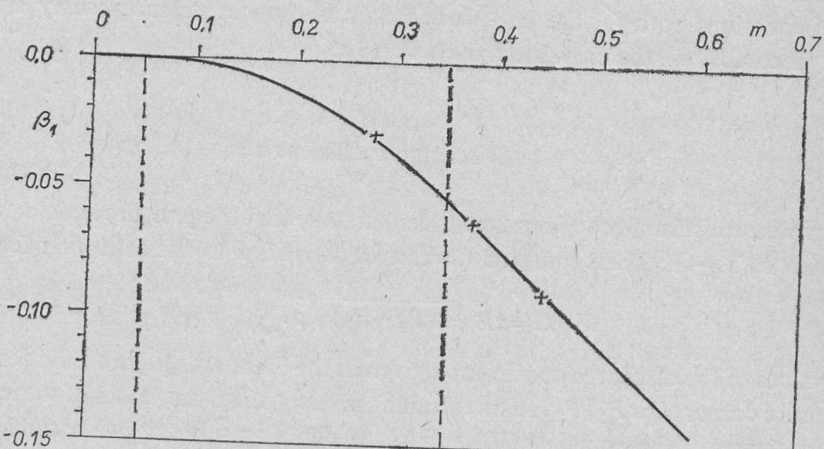

Fig. 1. Coefficient $\beta_1=\beta_1(m)$ for a nozzle

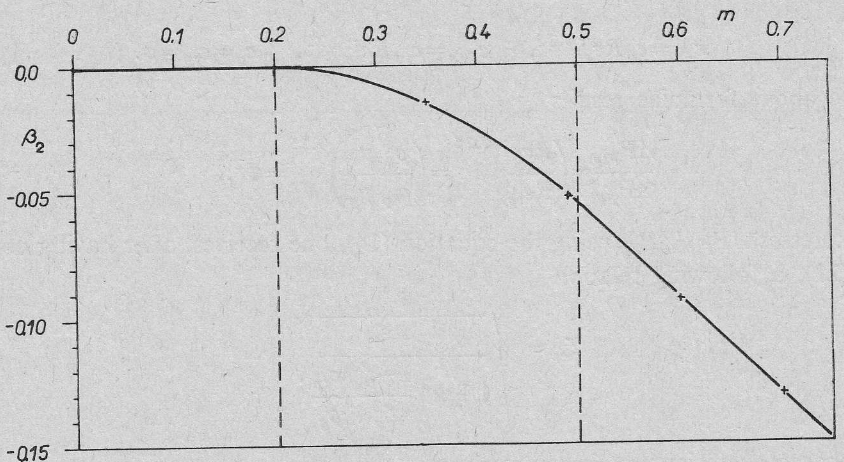

Fig. 2. Coefficient $\beta_1 = \beta_1(m)$ for an orifice plate

If the equation (14) for the flow without losses between the cross-section of $\varnothing D$ and $\varnothing d$ is expressed by means of Bernoulli's equation the relation defining the discharge coefficient takes a form

$$\alpha_B = \frac{\mu}{\sqrt{1-\mu^2 m^2}} \tag{15}$$

and the flow rate can be consequently expressed by the formula

$$G = \alpha_B F \sqrt{2(P_1^* - P_2^*)}\sqrt{\rho_{tp}}\,. \tag{16}$$

Comparing the formulae (3), (15) and (14), (16) one receives

$$\alpha = \frac{\zeta}{B}\alpha_B, \quad \text{where} \quad B = \frac{1}{\sqrt{1+\beta_1-\beta_2}}\,. \tag{17}$$

The difference of the pressures $\Delta P^* = P_1^* - P_2^*$ indicates the "pressure drop" in a flow without losses. For a real flow there is analogously $\Delta P' = P_1' - P_2'$. The difference $\Delta P' - \Delta P^* = \Delta P_F$ represents the friction losses between the cross-sections $\varnothing D$ and $\varnothing d$. From the equations (10), (16), (15) and (17) the following relation results

$$\Delta P_F = \left(\frac{1}{\zeta^2} - 1\right)\frac{1}{2\rho}\left(\frac{G}{\alpha_B F}\right)^2. \tag{18}$$

The equation (18) applies clearly both to the flow of one-phase fluid and to the flow of two-phase fluid. The friction losses ΔP_F are proportional to the friction coefficient c_F. To the turbulent flow of fluid flowing through the cylindrical pipes the following equation can be applied

$$c_F = cRe^{-0{,}25}. \tag{19}$$

In the assumed range of the pressures and the relative dryness values (Tab. 1) the volume concentration coefficient has a high value and therefore the following assumptions are justified

$$c_{Fg}=c_g\,Re_g^{-0.25}, \quad c_{Ftp}=c_{tp}\,Re_{tp}^{-0.25}, \quad c_g=c_{tp}=c\,. \tag{20}$$

From the above formulae results

$$\frac{\Delta P_{Ftp}}{\Delta P_{Fg}}=\left(\frac{Re_g}{Re_{tp}}\right)^{0.25}=\left(\frac{\rho_g}{\rho_{tp}}\frac{\mu_{tp}}{\mu_g}\right)^{0.25}=\Phi^2. \tag{21}$$

If one expresses $\Delta P_{Ftp}/\Delta P_{Fg}$ using the equation (14), one receives, after having compared it with (21), a following relation

$$\zeta_{tp}=\sqrt{\frac{1}{1+\Phi^2\,\dfrac{1-\zeta_g^2}{\zeta_g^2}\,\dfrac{\rho_{tp}}{\rho_g}}}\,. \tag{22}$$

The discharge coefficient α_{tp} becomes then

$$\alpha_{tp}=\zeta_{tp}\,\frac{\alpha_B}{B}\,. \tag{23}$$

For calculating ζ_{tp} one has to determine ρ_{tp}, ζ_g and μ_{tp}. The specific mass ρ_{tp} of the wet steam is given by a known relation

$$\frac{1}{\rho_{tp}}=\frac{x}{\rho_g}+\frac{1-x}{\rho_f}\,. \tag{24}$$

The loss coefficient ζ_g can be easily calculated by introducing the known values of μ_g and α_g into (6) and (7) for any value of m.

The viscosity of the two-phase mixture μ_{tp} is being defined by the various relations [9]. In this paper the relation given by McAdams is used

$$\frac{1}{\mu_{tp}}=\frac{x}{\mu_g}+\frac{1-x}{\mu_f}\,. \tag{25}$$

The μ_{tp} follows almost exactly the changes of μ_g.

The values of α_{tp} for a nozzle and an orifice plate

The values of α_{tp} for a standard nozzle and an orifice plate [6] have been calculated using the equation (23) and are given in Tables 2 and 3 for pressures $p=0.05$, 0.5, 5.0, 50.0 bar and the relative dryness $x=0.95$, 0.90, 0.85, 0.80. As could be expected the values of α_{tp} are practically independent of the pressure p i.e. on Re numbers. The deviations from this regularity are overlapped by the basic tolerance value given in the Standards referring to the measurements of one-phase fluid.

The relation

$$\alpha_{tp}=\alpha_{tp}(m,x) \tag{26}$$

is plotted in Figs. 3 and 4.

Table 2

Values of the discharge coefficient $\alpha_{tp}=\alpha_{tp}(m, x, p)$ for a nozzle

	α_{tp}										
x \ m	0.05		0.20		0.35		0.50		0.65		p [bar]
0.95	0.986	4	0.998	1	1.028	2	1.080	6	1.182	2	0.05
						2		6		2	0.50
						2		6		2	5.00
						3		7		3	50.00
0.90	0.985	4	0.997	1	1.027	6	1.080	0	1.18	0 9	0.05
		5		1						1 0	0.50
		5		2						1 0	5.00
		6		2						1 1	50.00
0.85	0.984	4	0.996	0	1.02	6 8	1.079	3	1.179	5	0.05
		4		1		6 8		3		5	0.50
		5		1		6 9		3		6	5.00
		6		3		7 0		4		8	50.00
0.80	0.983	2	0.99	4 8	1.026	0	1.078	5	1.17	7 9	0.05
		3		4 8		0		5		8 0	0.50
		3		4 9		0		6		8 1	5.00
		6		5 2		2		7		8 4	50.00

Table 3

Values of the discharge coefficient $\alpha_{tp}=\alpha_{tp}(m, x, p)$ for an orifice plate

	α_{tp}										
x \ m	0.05		0.20		0.35		0.50		0.65		p [bar]
0.95	0.598	0	0.614	7	0.645	6	0.693	2	0.766	0	0.05
										0	0.50
										0	5.00
										2	50.00
0.90	0.597	9	0.614	5	0.64	4 9	0.691	6	0.76	2 8	0.05
						4 9		6		2 8	0.50
						4 9		7		2 9	5.00
						5 0		8		3 2	50.00
0.85	0.597	8	0.614	3	0.644	1	0.6	8 9 9	0.7	5 9 3	0.05
						1		9 0 0		5 9 4	0.50
						1		9 0 0		5 9 5	5.00
						2		9 0 3		6 0 0	50.00
0.80	0.597	7	0.614	0	0.643	2	0.688	1	0.75	5 4	0.05
		7		0		2		1		5 5	0.50
		8		1		3		2		5 7	5.00
		8		1		4		6		6 5	50.00

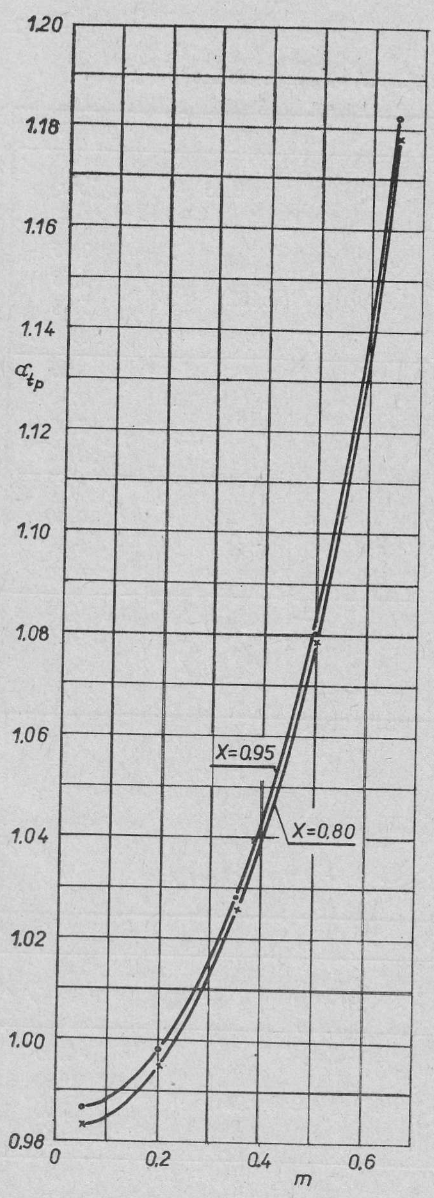

Fig. 3. Discharge coefficient $\alpha_{tp}=\alpha_{tp}(m, x)$ for a nozzle

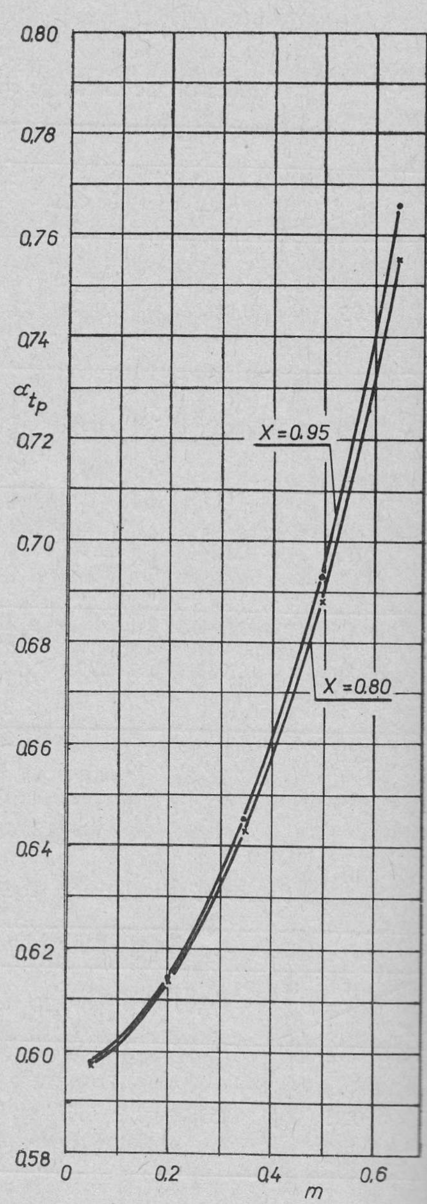

Fig. 4. Discharge coefficient $\alpha_{tp}=\alpha_{tp}(m, x)$ for an orifice

In the course of the numerical calculations of α_{tp} for $x=\text{const}$ the equation (26) has been approximated by a polynomial of the 4th degree

$$\alpha_{tp}=a_0+a_1 m+a_2 m^2+a_3 m^3+a_4 m^4. \tag{27}$$

The values of coefficients $a_0 \div a_4$ are given in Table 4. Where Table 3 gives different values α_{tp} for the individual pressure levels, mean aritthmetical value was used

Table 4

Values of coefficients $a_0 \div a_4$ appearing in the equation (27) for a nozzle and an orifice plate

	x	a_0	a_1	a_2	a_3	a_4
Nozzle	0.95	0.9893	−0.1051	1.0502	−1.8989	1.8991
	0.90	0.9885	−0.1102	1.0800	−1.9465	1.9176
	0.85	0.9878	−0.1171	1.1170	−2.0014	1.9362
	0.80	0.9869	−0.1247	1.1566	−2.0588	1.9547
Orifice plate	0.95	0.5960	0.0185	0.4394	−0.4243	0.4979
	0.90	0.5982	0.0215	0.4188	−0.3903	0.4671
	0.85	0.5985	0.0291	0.3677	−0.2885	0.3868
	0.80	0.5953	0.0334	0.3357	−0.2204	0.3272

for calculating the coefficients $a_0 \div a_4$. In the numerical calculations one may even determine the value of α_g (for given m) from the corresponding Standards for one-phase fluid flow [6] and find out the value of α_{tp}/α_g (for corresponding x and m) in Figs. 5 and 6.

Comparison of computation methods

The above described method has been compared with the already mentioned data gathered in [$1 \div 5$]. The comparison was done by calculating the flow rate measured by orifice plate for the parameter values given in Table 5.

Table 5

Set of parameters for calculations checking the method

Run No.	x	p [bar]	ΔP_{tp}[kp/m^2]	D [mm]	m
1	0.9	1	1000	100	0.2
2		40	2000		

The results of the calculation, together with the deviations from the parameter mean values are shown in Table 6.

Table 6

Results of the flow rate calculations — measurements carried out using an orifice plate (for the parameter values taken from Tab. 5)

Run No.		1		2	
		1 bar		40 bar	
	i	G_i [kg/h]	G_i/G_s	G [kg/h]	G_i/G_s
[3] James	1	391.30	1.0088	3334.38	1.0128
[4] Höft	2	378.11	0.9748	3243.63	0.9853
[5] Chisholm	3	388.63	1.0019	3278.12	0.9957
[6] Murdock,	4	400.54	1.0326	3357.37	1.0198
[7] Kačer	5	380.82	0.9818	3247.48	0.9864

$$G_s = \frac{\Sigma G_i}{5}$$

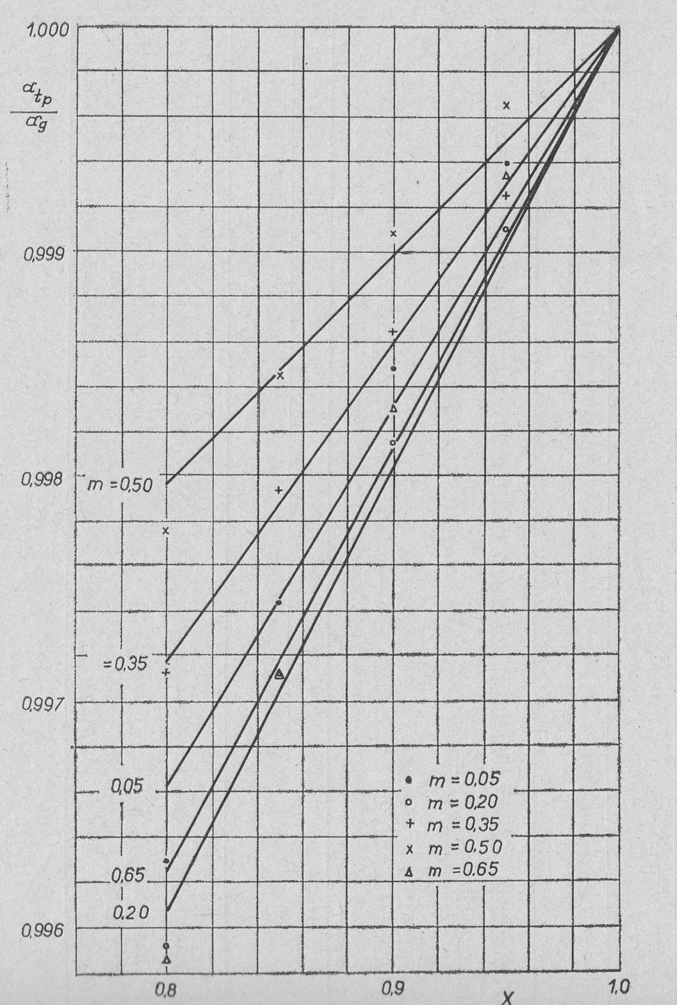

Fig. 5. Correction coefficient $\alpha_{tp}/\alpha_g = \alpha_{tp}/\alpha_g(x, m)$ for a nozzle

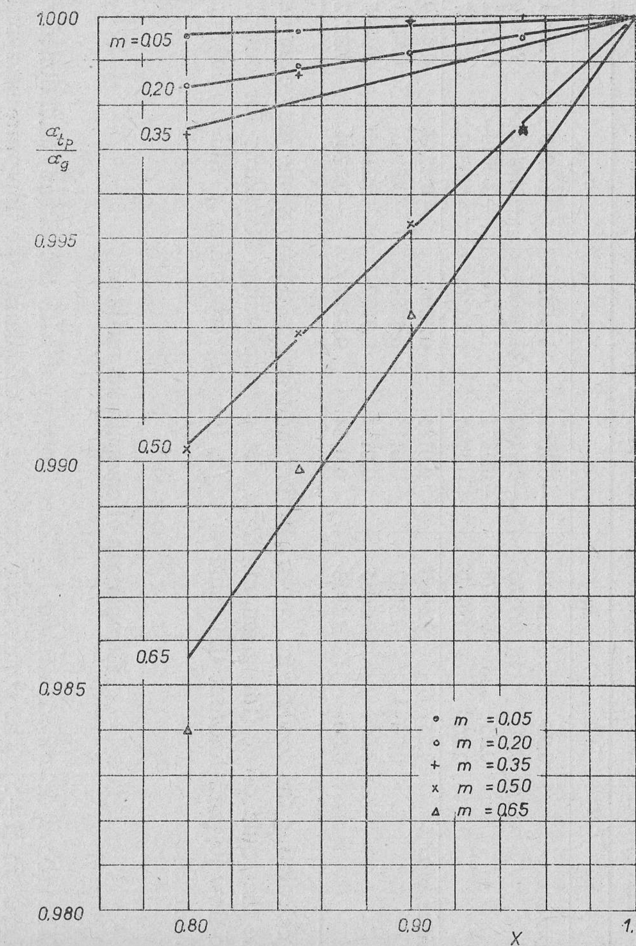

Fig. 6. Correction coefficient $\alpha_{tp}/\alpha_g = \alpha_{tp}/\alpha_g(x, m)$ for an orifice plate

It was impossible to carry out this comparison for pressures lower than 1 bar because some methods [3, 4] do not apply to these pressure values and an extrapolation would be needed.

The value of the maximum relative deviation of the individual methods from the mean G_s value exceeds several times the value of the basic tolerances for α_g values specified in the corresponding Standards [6] (for the one-phase fluid) and practically meets the accuracy ascribed by some authors [1, 2, 4] to their methods. With regard to the values of volume concentration coefficient α^* given in Table 1 it can be expected that the derived method will have its justification within the range of the parameter values defined by a dash line in this table. This line limits a zone in which $\alpha^* > 0.99$.

To decide which one of the existing methods gives a best picture of the real behaviour of the flow an experimental verification is required.

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Współczynnik wypływu mokrej pary wodnej dla standardowej dyszy i kryzy

Streszczenie

Przedstawiono metody obliczania współczynnika wypływu mokrej pary wodnej dla standardowej dyszy i kryzy, w zakresie ciśnień 0,05 – 50 bar i dla stopnia suchości $x > 0,8$. Wzory wyprowadzono na podstawie jednorodnego modelu przepływu dwufazowego, wychodząc z wartości współczynnika wypływu dla płynu jednofazowego. Do obliczania natężenia przepływu wykorzystano zależności formalnie takie same jak dla przepływu jednofazowego.

Współczynnik kontrakcji objętościowej ma wartość $\alpha^* > 0,99$ w zakresie ciśnień 0,05 – 50 bar dla stopnia suchości mokrej pary wodnej $x > 0,8$. Ten fakt przyjęto za podstawę rozważań; zakłada się, że w podanych granicach można modelować mokrą parę wodną za pomocą płynu jednorodnego o odpowiednich właściwościach.

Takie podejście stwarza możliwość wykorzystywania do obliczeń natężenia przepływu mokrej pary wodnej takich samych równań jak dla przepływu dwufazowego. Warunkiem koniecznym przy stosowaniu wyprowadzonych równań jest istnienie małych spadków ciśnienia w urządzeniu dławiącym,

co zapobiega powstaniu znaczniejszych zmian fazowych, jakie nie mogłyby być objęte modelem jednorodnym.

Wartość współczynnika wypływu dla dyszy lub kryzy, przez którą przepływa mokra para wodna określa się z wartości α_g dla płynu jednofazowego, podanej w stosownych przepisach. Wartość współczynnika strat przepływu koryguje się odpowiednio do własności fizycznych jednorodnego płynu reprezentującego parę mokrą. Tak więc dla danych m i x skorygowana wartość α_g jest równa

$$\alpha_{tp}=\alpha_{tp}(m, x).$$

Podano postaci wielomianów 4-go stopnia $\alpha_{tp}=\alpha_{tp}(m)$ dla $x=0{,}95$, $0{,}90$, $0{,}85$, $0{,}80$ i wykresy

$$\frac{\alpha_{tp}}{\alpha_g}=\frac{\alpha_{tp}}{\alpha_g}(x) \qquad \text{dla } m=\text{const}$$

dla standardowej dyszy oraz dla kryzy o ostrych krawędziach.

Na zakończenie porównano, na podstawie przykładu obliczeniowego, przedstawioną metodę z innymi metodami obliczeń.

Коэффициент расхода водяного пара для стандартных измерительных сопел и шайб

Резюме

Разработаны методы расчета коэффициента расхода влажного водяного пара для стандартных измерительных сопел и шайб, в диапазоне давлений 0,05 - 50 бар и для относительной сухости $x>0{,}8$. Метод разработан на основе однородной модели двухфазного течения, исходя из значения коэффициента расхода для однофазной жидкости. В расчетах расхода использованы формальные зависимости такие же, как и для однофазного течения.

Коэффициент объемного расхода достигает значения $\alpha^*>0{,}99$ в диапазоне давлений 0,05 - 50 бар для относительной сухости влажного пара $x>0{,}8$. Этот факт принят в основу рассуждений. Предполагается, что в определенных выше пределах можно влажный пар моделировать однородной жидкостью, характеризующейся соответствующими свойствами.

Такой подход к делу создает возможность использования для расчетов расхода влажного водяного пара, замеряемого при помощи стандартного измерительного сопла или шайбы, уравнений, форма которых такая же как и для двухфазного течения. Необходимым условием применения выведенных уравнений является наличие малых перепадов давления в дроссельном устройстве, что препятствует возникновению более значительных фазовых превращений, которые нельзя было бы зачислить к однородной модели.

Значение коэффициента расхода для измерительного сопла или шайбы, через которые течет влажный пар, выводится из значения α_g для однофазной жидкости, определенной соответствующими указаниями. Вычисляется коэффициент потерь течения для дроссельного устройства. Его значение корректируется в соответствии с физическими свойствами однородной жидкости, заменяющей влажный пар.

Итак, для известных значений m и x откорректированное значение α_g равняется

$$\alpha_{tp}=\alpha_{tp}(m, x).$$

Представлены формы многочленов четвертой степени $\alpha_{tp}=\alpha_{tp}(m)$ для $x=0{,}95$, $0{,}90$, $0{,}85$, $0{,}80$ и графики

$$\frac{\alpha_{tp}}{\alpha_g}=\frac{\alpha_{tp}}{\alpha_g}(x) \qquad \text{для } m=\text{const}$$

для стандартного измерительного сопла и для шайбы с острыми кромками.

В заключении дается расчетный пример и на его основе сравнивается представленный метод с существующими до сих пор методами.