BULETINUL Universității Petrol – Gaze din Ploiești	Vol. LIX No. 2/2008	43 - 50	Seria Tehnică

Hydrodynamic Effects of the Water Separation in the Curved Sections of the Natural Gas Pipes

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Abstract

The water separation from the natural gas transported through major pipes can be made by the means of the separators, or even through sections of curved pipe that gives the water particle a centrifugal effect. This type of effect depends on the geometrical characteristics of the curved section of the pipe, or separator, on the type of transportation for the gases in the pipe as well as on the specific mass differences between liquid water and natural gases which present the transporting element for the water particles found in the pipe.

Key words: *natural gas, water separation*, *curved pipe, centrifugal effect.*

The Hydrodynamics of the Water Separation Using Curved or Centrifugal Separators

The use of the separators in the shape of a tor sector may lead in certain situations at a good separation of the water from the gas body. A tor sector is represented in figure 1 where, through *d* we marked the interior diameter of the pipe, and through *R* a curved radius of the pipe's spindle.

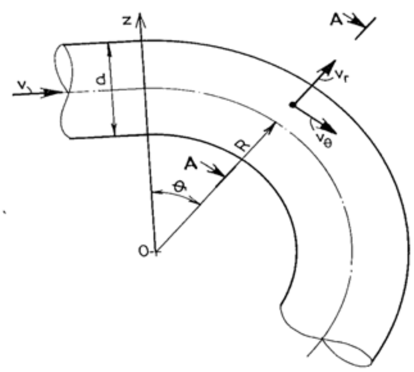

Fig. 1

In the case of such a separator, we must establish very clearly the influence the curved radius *R* can generate, the circle sector angle α on which it is developed the curved section of the pipe according to the gas speed at the entry in the separator. Such separator gives to the gases a circle movement, and, at their turn, they transfer it to the water.

In the curved section of the pipe a modification on the speed distribution occurs and its effect is the separation of the water from the gases mass. Thus, the speed compound v_z=0 and v_r and v_θ compounds are considered for the gases and v_{rp} and $\mathrm{v}_{\theta p}$ for the water particle.

The v_θ compound assimilated as being generated by the movement of a whirlpool with the centre in O and Γ intensity, the latter being determined from the fallowing equation. For a fixed value of the θ angle $\left(0 \le \theta \le \alpha\right)$, we can write the continuity equation in the following manner

$$\frac{\pi d^2}{4}\mathrm{v} = \iint\limits_{(A)} \mathrm{v}_\theta \mathrm{d} A, \tag{1}$$

where dA is the extent element perpendicular on the compound v_θ, v represents the advancement current speed before its entry in the curved area. Section A-A from figure 1 is rendered by figure 2.

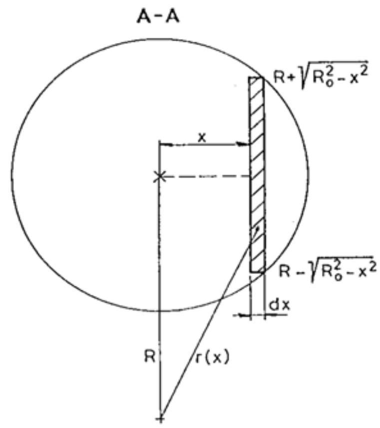

Fig. 2

The v_θ compound, as well as the radial v_r is determined admitting the fact that the movement in the curved area is generated by the complex potentiality

$$f\left(z\right) = +i\frac{\Gamma}{2\pi}\ln\left(z - iR\right) = +i\frac{\Gamma}{2\pi}\ln\left[x + i\left(y - R\right)\right] = +i\frac{\Gamma}{2\pi}\ln \bar{r}\, e^{i\theta} \tag{2}$$

where $r^2 = x^2 + \left(y - R\right)^2$, $\theta = \mathrm{arctg}\frac{y - R}{x}$, and $i = \sqrt{-1}$. Starting from (2) we immediately find the real part $\varphi = -\frac{\Gamma}{2\pi}\theta$ and the imaginary part $\Psi = +\frac{\Gamma}{2\pi}\ln r$, where φ and Ψ represent the speed's potential function and, respectively, the current function of the potential movement. The v_r and v_θ compounds have the fallowing values

$$\mathrm{v}_r = \frac{\partial\varphi}{\partial r} = 0;\ \mathrm{v}_\theta = \frac{1}{r}\frac{\partial\varphi}{\partial\theta} = -\frac{1}{r}\frac{\Gamma}{2\pi}. \tag{3}$$

The results obtained are identical with the ones given by the literature in the field [15, 21], where it is considered a null compound for the radial direction, and on the tangential direction the product $\mathrm{v}_r \cdot r = \text{constant}$.

The constant form the previous equality is calculated by the help of the continuity equation written under the form (1). The right member of the equation mentioned before becomes

$$\iint_{(A)} \mathrm{v}_\theta \mathrm{d}A = -\frac{\Gamma}{2\pi}\iint_{(A)} \frac{1}{r}\mathrm{d}A = -\frac{\Gamma}{2\pi}\int_{-R_0}^{R_0}\int_{R-\sqrt{R_0^2-x^2}}^{R+\sqrt{R_0^2-x^2}} \frac{1}{\sqrt{x^2+(y-R)^2}}\mathrm{d}y\,\mathrm{d}x, \tag{4}$$

where the following mark has been introduced $R_0 = d/2$.

The integral must be firstly made in relation with the *y* variable and then with *x*. As compared with the first variable, (*y*), the integral is easy to solve and can be found in

$$\iint_{(A)} \mathrm{v}_\theta \mathrm{d}A = -\frac{\Gamma}{2\pi}\int_{-R_0}^{R_0} \ln\frac{R_0+\sqrt{R_0^2-x^2}}{R_0-\sqrt{R_0^2-x^2}}\mathrm{d}x. \tag{5}$$

We can suppose that we do not introduce a too large error if we replace

$$\ln\frac{R_0+\sqrt{R_0^2-x^2}}{R_0-\sqrt{R_0^2-x^2}} \approx 2\frac{\sqrt{R_0^2-x^2}}{R_0-\sqrt{R_0^2-x^2}}, \tag{6}$$

which leads to the solving of the integral from (5). After a simple calculation we obtain the following result

$$\iint_{(A)} \mathrm{v}_\theta \mathrm{d}A = -\frac{\Gamma}{2\pi}(\pi+4)R_0. \tag{7}$$

Taking into consideration the equation (5), the value of the constant defining the intensity of the circulation results

$$\frac{\Gamma}{2\pi} = \frac{\pi}{\pi+4}R_0\mathrm{v} \tag{8}$$

and the absolute value of the tangential speed will be

$$\mathrm{v}_\theta = \frac{\pi}{\pi+4}\frac{R_0}{r}\mathrm{v}, \tag{9}$$

where the variable radius is situated between $R+\sqrt{R_0^2-x^2}$ and $R-\sqrt{R_0^2-x^2}$.

The conclusion is consequently that in the spindle of the curved pipe the average radius is *R* which renders

$$\mathrm{v}_\theta = \frac{\pi}{\pi+4}\frac{R_0}{R}\mathrm{v} \approx 0.44\frac{\mathrm{R}_0}{\mathrm{R}}\mathrm{v}. \tag{10}$$

The greatest speed (v_i) is obtained for $r = R - R_0$ and the weakest for (v_e) at $r = R + R_0$. This means that the ratio of the two speeds is

$$\frac{\mathrm{v}_e}{\mathrm{v}_i} = \frac{R-R_0}{R+R_0}. \tag{11}$$

The result previously obtained indicates that the more the curved radius *R* of the separator is reduced at the same dimension as the one of the pipe, the lower the tangential speed; precisely in certain cases $(R \le R_0)$ the v_e speed can have a negative value. This means that at very tight bends the particle can be given a vice-versa movement than the movement it fallowed when she entered the separator. This effect may be applied to the water particle when the radius of the transportation pipe is superior to the curved radius of the same pipe.

The Centrifugal Effect on the Separation of the Water Particles from the Gas Flow

In the situation previously accepted, namely that the separator lays in the horizontal position the movement equation written on the radial direction will be

$$m\frac{\mathrm{d}\,\mathrm{v}_{rp}}{\mathrm{d}t} = m\,r\,\omega^2\left(\frac{\rho_a-\rho}{\rho_a}\right) - \rho\frac{\left(\mathrm{v}_r-\mathrm{v}_{rp}\right)^2}{2}C_D\frac{\pi d_p^2}{4}, \tag{12}$$

where C_D is calculated by the help of one of the relations given in [18,21], namely:

$$C_D = \frac{24}{Re_p} \text{ for } Re_p < 2; \tag{13.a}$$

$$C_D = \frac{18}{\mathrm{Re}_p^{0.6}} \text{ for } 2 \le Re_p < 200; \tag{13.b}$$

$$C_D = \frac{24}{Re_p}\left(1+\frac{0{,}15}{Re_p^{0{,}687}}\right) \text{ for } 200 \le Re_p \le 800; \tag{13.c}$$

$$C_D = 0.44 \text{ for } 800 < Re_p. \tag{13.d}$$

If, instead of the mass we introduce $\pi d_p^3\left(\rho_a-\rho\right)/6$ it will immediately result the differential equation

$$\frac{\mathrm{d}\,\mathrm{v}_{rp}}{\mathrm{d}t} = r\,\omega^2 - \frac{3}{4}C_D\frac{\left(\mathrm{v}_r-\mathrm{v}_{rp}\right)^2}{\mathrm{d}\,p}\frac{\rho}{\rho_a-\rho}, \tag{14}$$

v_r stands for the radial speed of the fluid, v_{rp} –the radial speed of the particle and ω - the angle speed at which the water particle is subjected at.

The radial speed of the fluid can be neglected in relation to the one of the particle. The radius r stands for the radius at the material point of the turning spindle. As we have indicated already, $\mathrm{v}_r \approx 0$ or at least it has an extremely low value, consequently it can be immediately written as

$$\frac{\mathrm{d}\,\mathrm{v}_{rp}}{\mathrm{d}t} = r\,\omega^2 - \frac{3}{4}\frac{C_D}{(s-1)}\frac{\mathrm{v}_{rp}^2}{\mathrm{d}\,p}. \tag{15}$$

The C_D coefficient presents values corresponding to the four stages underlined by the Reynolds number Re_p, according to the formulas (13).

The differential equation (15) is integrated with the following initial conditions:

$$\text{at } t = 0,\ \frac{\mathrm{d}\,\mathrm{v}_{rp}}{\mathrm{d}t} = 0 \text{ and } \mathrm{v}_{rp} = \omega_0 \tag{16}$$

ω_0 is considered an angle reference speed. We notice that $\mathrm{v}_{rp} = \mathrm{d}r/\mathrm{d}t$, which makes possible the writing of the same equation under the form of

$$\frac{\mathrm{d}^2 \mathrm{v}_{rp}}{\mathrm{d}t^2} + \frac{18\nu}{(s-1)\mathrm{d}_p^2}\frac{\mathrm{d}\,\mathrm{v}_{rp}}{\mathrm{d}t} - \omega^2 \mathrm{v}_{rp} = 0\,. \tag{17}$$

Its solution is acknowledged by [12, 30] under the form

$$\mathrm{v}_{rp} = A\,e^{\alpha t} + B\,e^{\beta t}, \tag{18}$$

where A and B are two integration constants and

$$\alpha = -\frac{9\nu}{(s-1)d_p^2} + \sqrt{\frac{81\nu}{(s-1)d_p^2} + \omega^2} \tag{19}$$

$$\beta = -\frac{9\nu}{(s-1)d_p^2} - \sqrt{\frac{81\nu}{(s-1)d_p^2} + \omega^2} \tag{20}$$

which, in this way, are known.

Using the same initial conditions (16) the following integration constants result

$$A = -\omega_0\frac{\beta}{\alpha-\beta};\;\; B = \omega_0\frac{\alpha}{\alpha-\beta}$$

which makes that the particle speed in the radial direction to be

$$\mathrm{v}_{rp} = \frac{\omega_0}{\alpha-\beta}\left(\alpha\,e^{\beta t} - \beta\,e^{\alpha t}\right). \tag{21}$$

The equal distance with the interior diameter d of the pipe is travelled by the water particle in a T time$_r$ which satisfies the relation

$$d = \int_0^{Tr} \mathrm{v}_{rp}\mathrm{d}t \tag{22}$$

and if the expression of the speed in the last equation is replaced we get

$$d = \frac{\omega_0}{(\alpha-\beta)\alpha\beta}\left[\alpha^2\left(e^{\beta Tr}-1\right) - \beta^2\left(e^{\alpha Tr}-1\right)\right]. \tag{23}$$

The exponential are approximated according to the rapport frequently used in engineering calculations, namely $e^x \approx 1 + x$, so that the result is that d has the following expression

$$d = \omega_0 T_r\,. \tag{24}$$

On the other side, in the T_r time period the particle travels the l_a length that can be calculated with a great precision by using the relations established according to the Reynolds number of the Re_p particle.

If we acknowledge that we can use the relation

$$l_1 = \mathrm{v}T + \frac{\mathrm{v}-\mathrm{v}_{p0}}{1.0204\,K_n}\left(1 - \mathrm{e}^{1.0204\,\mathrm{K_n}T}\right), \tag{25}$$

then the length of the arc l_a is equal to l_1 given by the relation

$$l_{1a} = \mathrm{v}_{p0}T\,. \tag{26}$$

In the case in which for l_1, it is chosen the same approximate value, meaning l_{1a}, then the size order of the arc's length l_a is

$$l_a \sim d \frac{\mathrm{v}_{p0}}{\omega_0}. \tag{27}$$

The minimum angle at the centre $\alpha_{\min}$ can be replaced in the previous relation because $l_a = \alpha_{\min} R$ and, thus we have

$$\alpha_{\min} \geq \frac{d}{R} \frac{\mathrm{v}_{p0}}{\omega_0}. \tag{28}$$

Consequently, we may understand that a separator made of a curved pipe with a radius R with a circular section becomes efficient only if the angle at the centre α satisfies the condition (28). This presumption raises problems related to the initial speed ω_0, because for v_{p0} we can take, for the safety of the calculations, even the average speed of the gases in the section of the pipe.

As for the measure order of the speed ω_0, we can apply the impulse conservation theorem in the initial moment, and the result is summed up by the following formula

$$(\rho_s - \rho) \frac{\pi d_p^2}{4} \omega_0^2 = (\rho_s - \rho) \frac{\pi d_p^3}{6} \frac{\mathrm{v}^2}{R}, \tag{29}$$

which leads to the relation

$$\left(\frac{\omega_0}{\mathrm{v}}\right)^2 = \left(\frac{2}{3} \frac{\mathrm{d}p}{R}\right), \tag{30}$$

where we have accepted that the tangential speed is equal to the average speed of the v gas.

Consequently, the minimum angle, $\alpha_{\min}$ will be of at least

$$\alpha_{\min} \geq \frac{d}{R} \sqrt{\frac{3}{2} \frac{R}{d_p}}. \tag{31}$$

By appreciating the value of the water particle, of the pipe's diameter and of the curved radius, for example, d_p=0.006 m, d=0.4 m and R=1.2 m, we have as a result the value of the angle

$$\alpha_{\min} = \frac{0.4}{1.2} \sqrt{\frac{3}{2} \times \frac{1,2}{0.006}} = 5.774 \text{ rad}.$$

If d_p=0.004 m and the other measures remain unchanged it results that $\alpha_{\min}$=7.071 rad. The results depend on the three variables (d, R and d_p). Amongst these, the most difficult estimation is to be made for the particle's diameter, d_p. If this variable grows, the angle $\alpha_{\min}$ is reduced, which means that the force put on the particle grows and vice versa, if d_p tends toward zero $\alpha_{\min}$ will have very high values.

In the same time, we can easily notice the fact that the curved infinite radiuses $\alpha_{\min}$ present very high values which means that the effect of the centrifugal separation is null.

The existence of a curved area makes that the specific section of the pipe to produce a supplementary loss of pressure which can be calculated by the classical relation

$$\Delta p = \rho \frac{\mathrm{v}^2}{2} \xi, \tag{32}$$

where the local strength coefficient ξ is determined for the case in which $d \leq 2R \leq 5d$, using the relation [2, 16]

$$\xi = \left[0.31 + 0.16\left(\frac{d}{R}\right)^{3.5}\right]\frac{\alpha^0}{90^0}. \tag{33}$$

For a curved area it is possible to apply the calculation formula $\Delta p = \rho\frac{v^2}{2}\frac{l}{d}\lambda$, where the hydraulic strength coefficient λ is determined by the use of the relation

$$\frac{\lambda}{4}\left(2\frac{R}{d}\right)^{1/2} = 0.00725 + 0.076\left[\mathrm{Re}\cdot\left(\frac{d}{2R}\right)^2\right]^{-1/4}. \tag{34}$$

The results obtain by the intermediary of the previous relation are in a good agreement with the experiments for the situation in which

$$0.034 < \mathrm{Re}\left(\frac{d}{2R}\right)^2 < 300, \tag{35}$$

Re being considered to be the Reynolds number defined by the average speed of the gas and the interior diameter of the pipe. For lower values than 0.034 of the $Re\left(\frac{d}{2R}\right)^2$ parameter the hydraulic strength parameter can be calculated from a rectilinear pipe.

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Efecte hidrodinamice la separarea apei în secțiunile curbe ale conductelor de gaze naturale

Rezumat

Separarea apei se poate efectua utilizând separatoare, sau chiar porțiuni din conductă, de formă curbă care imprimă particulei de apă un efect centrifugal. Acest efect este dependent de caracteristicile geometrice ale porțiunii curbe din conductă, de regimul de transport al gazelor prin conductă precum şi de diferența de greutate specifică dintre apa lichidă şi gazele naturale care reprezintă pentru particulele de apă elementul transportor din conductă.