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Journal of Hazardous Materials B81 (2001) 123–140

Journal of Hazardous Materials

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Evaluation of the models available for the prediction of pressure drop in venturi scrubbers

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Received 19 May 2000; received in revised form 5 October 2000; accepted 6 October 2000

Abstract

The major running cost derived from the operation of venturi scrubbers is pressure drop. In the present study, the predictions of different models are compared to experimental data from venturi scrubbers of different sizes (throat diameter from 1.9 to 16 cm), geometries, operating variables and liquid injection arrangements. As a result, it is concluded that most of the models must be used with caution. Much attention must be paid to the validity of the assumptions employed in the mathematical models. The equations proposed by Calvert [Scrubbing, Air Pollution, 3rd Edition, Vol. IV, Academic Press, New York, 1982], Yung et al. [JAPCA 27 (1977) 348] or Hesketh [Atomization and cloud behaviour in wet scrubbers, in: Proceedings of the US–USSR Symposium Control Fine Particulate Emissions 1974, San Francisco, 15–18 January 1974] produce good results only in very specific situations. The model proposed by Boll [Ind. Eng. Chem. Fundam. 12 (1973) 40] is simple, easy to compute and agrees reasonably well with the experimental data. Unfortunately, it cannot predict the effect of different liquid injection arrangements. The model by Azzopardi and coworkers [Filtr. Sep. 21 (1984) 196; Trans. IchemE. 69B (1991) 237; Chem Eng. J. 67 (1997) 9] was the only one to give good predictions for all the range of variables studied. On the other hand, this model is not simple and requires from the engineer an additional effort in terms of computation. In order to apply this model to the rectangular geometry, the concept of hydraulic equivalent diameter was used.

Keywords: Venturi scrubber; Pressure drop; Gas cleaning; Modeling

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0304-3894/01/$ – see front matter
PII: S0304-3894(00)00336-8

1. Introduction

Regulations controlling the emissions of pollutants into the atmosphere are becoming more and more strict. In order to accomplish with these constraints the development of new technologies is necessary, as well as the improvement of those already existing. One of most efficient devices for the removal of very small particles from gaseous streams is the venturi scrubber [8]. In consequence, these devices have been subjects of numerous studies, particularly in the recent years. Venturi scrubbers are robust and simple, can be used with acid and corrosive gases, as well as sticky particles [9]. They can reach very high efficiencies for very small particles (0.3–5.0 μm). These particles are very harmful because they deposit on the human lungs and breathing system [10]. As a secondary process it can perform the absorption of a soluble gas pollutant [11].

All these advantages are obscured by a very high running cost in terms of pressure drop [8]. Pressure drop is the main economic consideration, and combined with the efficiency it usually determines the most convenient operating conditions. It is not surprising that a usual way of expressing efficiency in venturi scrubbers is the ratio of collection to pressure drop. In consequence, the study of pressure drop in venturi scrubbers requires special attention.

The estimation of pressure drop in venturi scrubbers is not trivial. The engineer can find equations and techniques developed during the last three decades. Some of these equations can lead to errors as high as 100%, as will be shown later. More sophisticated models give better results, but they require an investment in terms of time and computational effort.

The objective of this work is to describe and evaluate the most important models available for the prediction of pressure drop in venturi scrubbers. Special attention has been paid to the assumptions of each model in order to justify the validity of the equations under different circumstances. In addition, experimental data is compared to the predictions of these models, covering a variety of situations and operating conditions. The present authors directly collected part of the experimental data of pressure drop, while the rest was obtained from published literature.

2. Theory

A venturi scrubber is constituted of three main parts (Fig. 1), convergence, throat, and diffuser or divergence. As the section of the venturi decreases in the convergence, the gas carrying a particulate contaminant is accelerated to a velocity in the order of 50–120 m/s. Liquid can be introduced somewhere along the venturi or even upstream, although the preferred places are the end of the convergence and the throat. In any event, the high kinetic energy of the gas atomises the liquid into very small drops. Initially these drops are flowing very

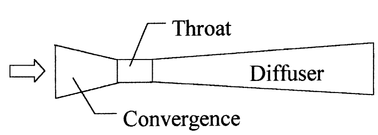

Fig. 1. Schematic representation of a venturi.

slowly, and there is a large difference in velocity between the drops and the gas. The drops behave as very efficient inertial collectors, and the particles are transferred from the gas to the liquid [12]. In the diffuser the gas decelerates and a part of the pressure lost is recovered.

Azzopardi and Govan [5] identified the mechanisms causing pressure drop in venturi scrubbers:

(a) *Momentum change of the gas*. The gas is accelerated in the convergent section. As the velocity of the gas raises pressure decreases as described by the equation of Bernouilli. The opposite effect takes place in the diffuser, but pressure recovery in the diffuser is not complete due to gas turbulence, growth and detachment of the boundary layer. This phenomenon is typical of divergence sections, and its effect increases as the angle of the diffuser raises.

(b) *Momentum change of the drops.* The scrubbing liquid can be introduced as jets or as a film, or combined. In any case, a fraction of the liquid will flow as a spray of small drops, while the rest will flow as a film on the walls of the venturi [13,14]. Initially drops are flowing slowly, but they accelerate almost immediately. This acceleration is enhanced by the high relative velocity between the drops and the gas, which creates the drag that accelerates the drops. The energy spent in this process is lost in form of gas pressure drop. Drops can be also decelerated in the diffuser. However, the deceleration of drops is slower than that of the gas, due to their higher inertia. In any event, it is possible that some pressure can be recovered due to the deceleration of drops in the divergence.

(c) *Momentum change of the film*. The fraction of liquid flowing as a film can be also accelerated, mainly caused by the drag film-gas. The energy spent in this acceleration is lost as gas pressure drop as well.

(d) *Friction*. The flow of a fluid in a pipe generates pressure drop due to the friction gas-walls. In this case, pressure drop will be increased by the effect of the film. The film forms a wavy surface that produces higher friction than a normal smooth wall.

(e) *Gravity*. If the equipment is built in such a way that the flow is not horizontal there is some small static pressure change. However, gravitational effects in venturi scrubbers are very small compared to inertial.

The relative importance of all these terms depends on the specific situation. In general, the energy lost due to mechanisms (c) and (e) is relatively small when compared to the others. These terms can be neglected with no significant error. In situations of practical interest mechanism (b) accounts for 50–85% of total pressure drop. As this is usually the main mechanism, it is not surprising that some models only include the pressure drop spent in the acceleration of the drops. Mechanism (d) can be very significant if the section of the venturi is small or the quantity of water atomised low. This last situation is likely to occur when the liquid to gas ratio is low or most of the liquid is flowing as a film. This is not unusual in laboratory-scale and pilot-scale venturi scrubbers, particularly when liquid is introduced as a film [13]. The importance of mechanism (a) increases with the angle of the divergence. It is usual to work with a divergence half-angle of 7° in order to minimise the effect of mechanism (a). If a venturi is not well designed this mechanism of pressure drop can be very important.

Fig. 2 shows the results of the simulation of pressure drop for two venturis of different scale, using the model of Boll [4]. This figure illustrates the relative importance of pressure

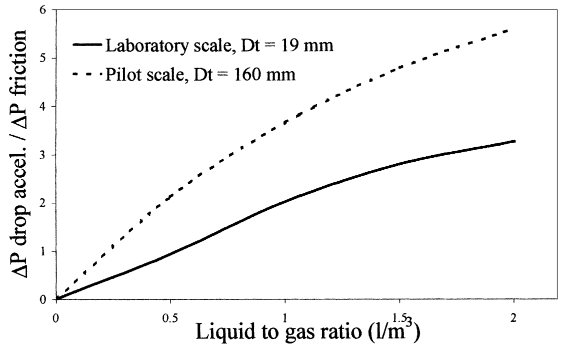

Fig. 2. Relative importance of mechanisms causing pressure drop, drop acceleration and friction of gas with wall or film. Calculations were performed using model of Boll [4].

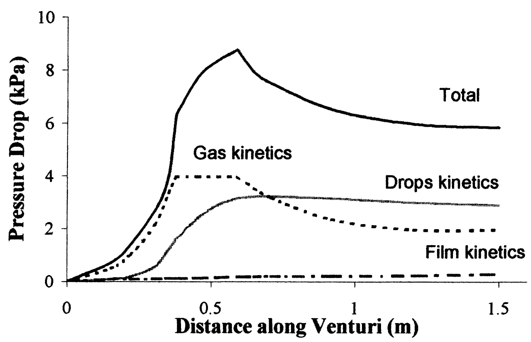

Fig. 3. Contribution of the three mechanisms of pressure drop in a venturi scrubber. Simulation performed using model of Azzopardi et al. [6], for the venturi of Allen and Van Santen [19], $U_G = 89$ m/s, liquid to gas ratio $= 1.01$ l/m^3.

drop caused by drop acceleration and friction. Fig. 3 shows a typical profile of pressure drop along a venturi scrubber [6]. The profile of mechanisms (a), (b) and (d) are included as well. Total pressure drop is obtained by the addition of the values of all the mechanisms.

3. Description of models

3.1. Equation of Calvert

The equation developed by Calvert [1,15] is probably the most popular among engineers. The success of his work is mainly due to its simplicity. Calvert [15] assumed the following hypothesis:

- The acceleration of drops at the throat is the main term of pressure drop. The other mechanisms discussed, plus the acceleration and deceleration of drops in the divergence can be neglected.

- All the liquid introduced is atomised into drops.
- There is no mass exchange between phases.
- All the drops have no initial axial velocity.
- Drops reach the velocity of the gas at some point in the throat.
- The velocity of the gas in the throat is constant.
- The flow is one-dimensional, incompressible and adiabatic.

Following these assumptions, a momentum balance for a differential of volume in the throat gives

$$-\mathrm{d}P = \rho_\mathrm{L} U_\mathrm{G} \frac{L}{G}\, \mathrm{d}U_\mathrm{D} \tag{1}$$

where U_G and U_D are, respectively, the gas and drop velocities, P denotes the pressure, ρ_L the liquid density, L and G are, respectively, the liquid and gas volumetric flow rate. Eq. (1) leads, upon integration, to

$$-\Delta P = P_1 - P_2 = \rho_\mathrm{L} U_\mathrm{G}^2 \frac{L}{G} \tag{2}$$

Calvert [1] observed that Eq. (2) "predicts roughly a 15% higher pressure drop than experimentally measured except at low liquid rates . . . ". For this reason, it has been suggested [16] that Calvert intended his equation to be used with a 0.85 multiplier factor. Most authors [17–19], however, do not add this factor when using or referring to Calvert's model [1], a procedure also adopted in the present paper.

New equations were proposed starting from Calvert's model [1], keeping the main assumptions, but refining the acceleration of drops. All of them considered drop acceleration as the only contribution to pressure drop. Yung et al. [2] and Leith et al. [20] are two illustrative examples, which will be described briefly here.

3.2. Model of Yung et al.

The model of Yung et al. [2], co-signed by Calvert, had its origin on the observation that drop do not always reach the velocity of the gas at the throat. In a real case, the velocity of drops at the end of the throat is lower than that of the gas at that point. This fact would explain why Eq. (2) would tend to overestimate pressure drop.

Using the correlation proposed by Hollands and Goel [21] for the drag coefficient of drops, and the correlation from Nukiyama and Tanasawa [22] for drop diameter, assuming drops of a single diameter, injection as jets at the beginning of the throat, and immediate atomisation of the liquid, Yung et al. [2] calculated analytically the velocity of drops at the end of the throat (U_Df):

$$U_\mathrm{Df} = 2U_\mathrm{G}(1 - X^2 + \sqrt{X^4 - X^2}) \tag{3}$$

where X is a dimensionless parameter defined as

$$X = \frac{3 l_\mathrm{t} C_\mathrm{Da} \rho_\mathrm{G}}{16 D_\mathrm{D} \rho_\mathrm{L}} + 1 \tag{4}$$

where C_{Da} is the drag coefficient for the drops in accelerated movement and D_{D} is the drop diameter. Defining a dimensionless parameter β as

$$\beta = 2(1 - X^2 + \sqrt{X^4 - X^2}) \tag{5}$$

we can write the equation of Yung et al. [2], applicable by definition to jet injection at the beginning of the throat, in this form

$$-\Delta P = \beta \rho_{\mathrm{L}} U_{\mathrm{G}}^2 \frac{L}{G} \tag{6}$$

3.3. Model of Leith et al.

Leith et al. [20] extended the work presented by Yung et al. [2] in order to include the pressure recovery due to the deceleration of drops in the diffuser. Their final equation is

$$-\Delta P = \rho_{\mathrm{L}} U_{\mathrm{G}}^2 \frac{L}{G} \left[\beta \left(1 - \frac{U_{\mathrm{Gf}}}{U_{\mathrm{Gt}}} \right) + \left(\frac{U_{\mathrm{Gf}}}{U_{\mathrm{Gt}}} \right)^2 \right] \tag{7}$$

where U_{Gf} and U_{Gt} are, respectively, the gas velocity at the end of the diffuser and at the throat of the venturi scrubber, and β is defined by Eq. (5).

3.4. Correlation from Hesketh

The correlation proposed by Hesketh [3] is portrayed here as one of those empirical equations that try to fit experimental data without any excessive theoretical justification. His equation is

$$-\Delta P = 190 \rho_{\mathrm{G}} U_{\mathrm{G}}^2 A_{\mathrm{t}}^{0.133} \left(\frac{L}{G} \right)^{0.78} \tag{8}$$

where the pressure drop ΔP is obtained in kPa if ρ_{G} is in kg/m^3, U_{G} is in m/s, the throat area A_{t} is in m^2 and L/G is a dimensionless liquid to gas volumetric ratio.

3.5. The model by Boll

Boll [4] was the first author to develop numerical solution to the problem of pressure drop in venturi scrubbers. As a result of this sophistication he was able to eliminate some restrictive assumptions included in the equation proposed by Calvert [1]. His model included a real integration of pressure drop along the equipment.

His model assumes three of the five mechanisms previously discussed, namely acceleration of the gas, acceleration of drops and friction wall-gas. From the assumption of a one-dimensional flow he proposed this differential equation for the momentum balance along the scrubber:

$$-\frac{\mathrm{d}P}{\rho_{\mathrm{G}}} = U_{\mathrm{G}}\,\mathrm{d}U_{\mathrm{G}} + mU_{\mathrm{G}}\,\mathrm{d}U_{\mathrm{D}} + \frac{(m+1)fU_{\mathrm{G}}^2\,\mathrm{d}x}{2D_{\mathrm{e}}} \tag{9}$$

where ρ_G is the gas density, m the dimensionless liquid/gas mass ratio, f denotes the friction factor used in the calculation of the shear stress gas/wall, and D_e represents the duct hydraulic equivalent diameter.

It can be observed from Eq. (9) that Boll [4] assumed complete atomisation of the liquid. In order to calculate the friction wall-gas he proposed the hypothesis of one-phase flow with average fluid density $(m + 1)\rho_G$. Boll [4] discussed briefly the fact that drops are continuously deposited and entrained onto and from the walls. This observation would suggest an additional term in his momentum equation, but he argues that his third term in Eq. (9) should be higher than the real friction, compensating the lack of additional terms in his equation.

The integration of Eq. (9) can be performed numerically along the scrubber, and not only the throat. The model allows for the possibility of liquid injection at any point, convergence, throat or diffuser. The atomisation of liquid is considered immediate. The calculation of the velocity of the gas is performed assuming incompressible flow and neglecting the effect of the growth of the boundary layer. The drops are assumed mono-dispersed spheres of diameter given by the equation from Nukiyama and Tanasawa [22]. The drag coefficient on the drops is calculated from the standard drag coefficient for spheres. Boll [4] discussed in detail these hypotheses concluding that they are reasonable except the drop diameter. As there was no better estimation for the drop size he was forced to use the equation proposed by Nukiyama and Tanasawa.

3.6. The model by Hollands and Goel

Although the model proposed by Boll [4] was a clear advance compared to the equation proposed by Calvert [1], it required a certain effort in terms of numerical integration. This problem was at that time not so easy to solve as it is nowadays. This reason motivated that Hollands and Goel [21] solved Boll's model [4] in terms of dimensionless numbers and presented the data in charts ready to use for the engineer. This tool allowed the possibility of using Boll's model [4] without the requirement of the numerical integration.

3.7. The model of Azzopardi and coworkers

The model of Azzopardi and coworkers [5–7] was basically developed in two stages. In the first stage the knowledge acquired by Azzopardi and Govan in annular two-phase flow was adapted to venturi scrubbers [5]. Annular flow is characterised by the existence of a film flowing on the walls of the equipment and a gas with drops flowing in the core. Azzopardi and Govan [5] observed that the nature of hydrodynamics in venturi scrubbers could be described in a similar manner.

The main feature in this model is the exchange of liquid between film and gas core. New drops are continuously stripped off from the film, called entrainment, while other drops are deposited onto the film. Taking this into account they were able to develop mass balances for film and liquid in the core, being able to estimate the split film-gas core at each position along the scrubber. Their mass balance on the film leads to

$$\frac{\mathrm{d}W_f}{\mathrm{d}x} = \pi D(F_{dep} - F_{ent}) \tag{10}$$

where W_f is the mass flow rate of the liquid film, D the duct diameter, F_{dep} and F_{ent} are, respectively, the flux of deposition of liquid onto the film and the flux of liquid entrained from the film, and x denotes the distance along the venturi axis.

The initial flow of film is introduced as a parameter into the model, and it will depend on the liquid injection arrangement. From this point the model is able to calculate the fluxes of entrainment and deposition by means of equations of this kind

$$F = KC_{drops} \tag{11}$$

where K is a constant of mass transfer obtained from empirical data in two-phase annular flow and C_{drops} denote the concentration of drops. After the calculation of the fluxes of entrainment and deposition it is possible to evaluate the liquid film flow using Eq. (10). A numerical integration of these equations leads to the estimation of film flow at any point along the venturi.

Additionally, their model allows for the existence of drops of different sizes depending on the point and manner they were created. The velocities of the drops are different for each group n. If the mechanisms of film acceleration and gravity are neglected this momentum balance is obtained:

$$-\frac{dP}{dx} = \rho_G H_G U_G \frac{dU_G}{dx} + \rho_L \sum_{i=1}^{n} H_{D,i} U_{D,i} \frac{dU_{D,i}}{dx} + \frac{4\tau_w}{d_e} \tag{12}$$

where H_G denotes the holdup or volumetric fraction of gas, $H_{D,i}$ and $U_{D,i}$ are, respectively, the volumetric fraction and the velocity of drops of group i, τ_w denotes the shear stress at the interface gas/film, d_e is the duct equivalent diameter taking into account the film thickness.

Azzopardi et. al. [6] observed that the model performed reasonable well up to the end of the throat, but did not predict so accurately in the diffuser. Pressure recovery in the diffuser was lower than what their model suggested. Following this, Teixeira [23] and Azzopardi et al. [6] extended the model in order to include the effect of the growth of the boundary layer in the diffuser. The result is a lower pressure recovery in the divergence than compared to their previous model, or that of Boll [4], as illustrated in Fig. 7.

This model represents the flow in a venturi scrubber quite realistically. On the other hand, it requires many equations and needs more complicated algorithms than those models presented so far. A detailed description of this model can be found in the work of Pulley [7].

This phenomenological model and some of its intrinsic correlations were developed specifically for the cylindrical geometry and therefore its authors do not recommend its application to rectangular venturi scrubbers. In this paper, however, a concept of *hydraulic equivalent venturi scrubber* (HEV) was used in order to apply this model to a rectangular geometry. An hydraulic equivalent venturi scrubber is defined here as a cylindrical equipment which has the following characteristics:

- The inlet, throat and outlet diameters are the equivalent hydraulic diameter of the inlet, throat and outlet rectangular cross-sections, that is, equal to four times the cross-section area divided by its perimeter.
- The gas and liquid flow through the HEV is such as to maintain the same throat gas velocity and volumetric liquid-to-gas ratio as in the rectangular venturi.

3.8. Model of Viswanathan et al.

Other models and equations are available in order to calculate pressure drop in venturi scrubbers. Among those, the model proposed by Viswanathan et al. [18] is one of the most interesting. Following the ideas of Azzopardi and coworkers [5], Viswanathan et al. [18] tried to describe the flow in a venturi scrubber in a very similar manner to that of two-phase annular flow. This model also includes the feature of film flow, with part of the water flowing as drops in the gas core and the rest as a film on the walls of the equipment. This model appears simpler to implement than that of Azzopardi and coworkers [5–7]. Unfortunately, Viswanathan et al. [18] did not provide any tool for the estimation of the fraction of liquid flowing as a film. In fact, they introduced this parameter in their model using their own empirical data. Consequently, unless the film flow is measured experimentally, or the fraction of water is estimated somehow (e.g. using model of Azzopardi and coworkers) there is a parameter lacking in order to implement this model. In any event, it appears quite clearly that the importance of the fraction of water flowing as a film is necessary if accurate estimations of pressure drop are required. Some improvements concerning this aspect have been recently presented, although further work in this direction is still necessary [13,14].

4. Methods and performance

In order to evaluate correctly the different models it appears necessary to compare them against empirical data from venturi scrubbers of different sizes, liquid injection systems and operating conditions. Experimental results of pressure drop obtained by the present authors in their laboratories, together with data presented in other works has been collected for this purpose. Table 1 summarizes the operating conditions for each set of data. A detailed description of these experiments can be found in the original references.

In order to measure quantitatively the performance of a model, two simple performance indexes were defined. The first index, called deviation index, is a measure of how close the model predictions are to the experimental values, on an average. If n is the number of experimental data points obtained, then

$$\text{Deviation index} = \frac{\sum_{i=1}^{n}[\text{abs}(\text{Estimated}\,\Delta P - \text{Experimental}\,\Delta P)/(\text{Experimental}\,\Delta P)]_i}{n} \qquad (13)$$

Table 1
Main geometric characteristics and operating conditions of data employed for the comparison to models

Author	Geometry	Injection system	Throat area (cm^2)	Throat length (cm)	U_G (m/s)	L/G (l/m^3)
Gonçalves et al. [24]	Cylindrical	Film and jets	2.84	1.5, 6.4	50–90	0.5–2.0
Yung et al. [2]	Cylindrical	Jets	47.66	12.1, 42.5	41.1–65.3	1.1–3.0
Allen and Van Santen [19]	Cylindrical	Film	201.06	20.6	45–115	0.2–1.1
Gonçalves et al. [25]	Rectangular	Jets	8.40	6.3, 9.0, 14.0	58.3, 74.6	0.08–0.3

The second index, called tendency index, measures the tendency of a model to overestimate or underestimate the experimental data. If the tendency index is positive, the model tends to overestimate the data, and if it is negative, to underestimate:

$$\text{Tendency index} = \frac{\sum_{i=1}^{n}[(\text{Estimated } \Delta P - \text{Experimental } \Delta P)/(\text{Experimental } \Delta P)]_i}{n} \quad (14)$$

5. Results and discussion

5.1. Case 1: small-scale cylindrical venturi scrubber

The experimental data of Gonçalves et al. [24], who studied the effect of two different liquid injection arrangements in a small-scale cylindrical venturi scrubber, was compared to the models of Calvert [1], Boll [4], Yung et al. [2] and Azzopardi and coworkers [5–7]. Results can be observed in Figs. 4 and 5, and the performance indexes are listed in Table 2.

In a small venturi when liquid is introduced as a film the fraction of water atomised is typically as low as 5–25%. [13]. In consequence, it can be expected that those models

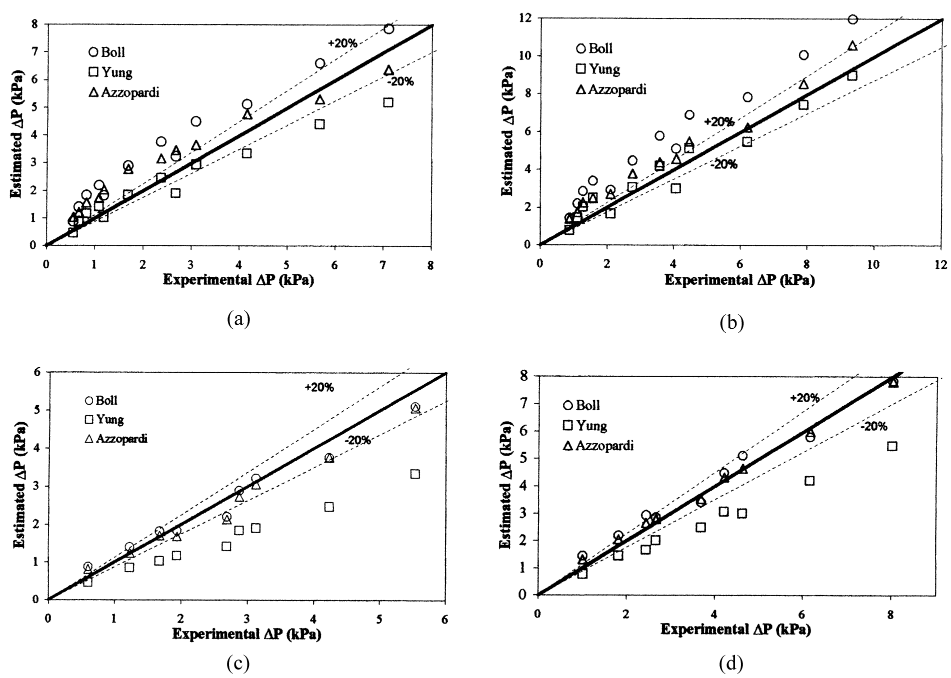

Fig. 4. Estimations of total pressure drop predicted by the models of Boll [4], Yung et al. [2] and Azzopardi and coworkers [5–7] against experimental data of Gonçalves et al. [24], for film injection (a, b), jet injection (c, d), and throat lengths of 1.5 cm (a, c) and 6.4 cm (b, d).

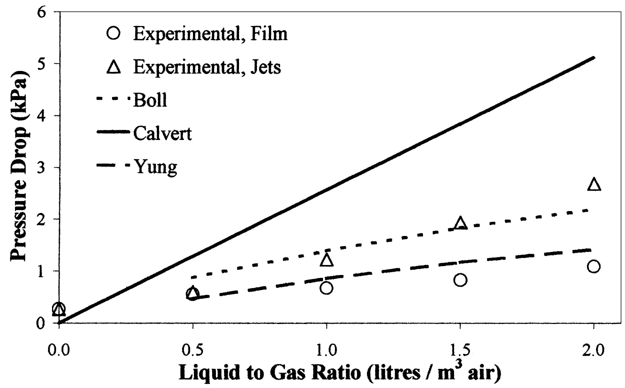

Fig. 5. Total pressure drop against liquid to gas ratio, for two types of liquid injection, $U_G = 50$ m/s, data from Gonçalves et al. [21].

Table 2
Deviation and tendency model performance indexes for the small-scale cylindrical venturi scrubber

Model	Index	Film injection smaller throat	Film injection longer throat	Jet injection smaller throat	Jet injection longer throat
Boll [4]	Deviation	0.57	0.60	0.13	0.13
	Tendency	+0.57	+0.60	+0.03	+0.10
Yung et al. [2]	Deviation	0.20	0.22	0.37	0.29
	Tendency	−0.02	+0.09	−0.37	−0.29
Azzopardi and coworkers [5–7]	Deviation	0.46	0.33	0.11	0.07
	Tendency	+0.44	+0.33	−0.02	+0.05

assuming total atomisation of the liquid considerably overestimate pressure drop due to drop acceleration. You can observe in Fig. 4(a) and (b) and in Table 2 that Boll's model [4] significantly overestimates the experimental data.

The model of Azzopardi and coworkers [5–7] does not assume complete atomisation. Consequently, the predictions obtained using this model are not as high as those predicted by Boll [4]. The equations proposed by Azzopardi and coworkers [5–7] still predict a higher film fraction, around 50% compared to values of around 25%. [13]. This could explain quite simply why this model would still tend to overestimate pressure drop, but not as much as Boll [4].

The good predictions of the model of Yung et al. [2] observed in Fig. 4(a) and (b) seem fortuitous in this specific case. This model assumes complete atomisation of the liquid as the model proposed by Boll [4]. In contrast, it does not consider the stress wall-gas. Consequently, neglecting the stress wall-gas compensates the overestimation of pressure drop due to liquid acceleration.

As it has been noted, the pressure loss due to friction gas-wall, or gas-film, is quite significant in small-scale venturi scrubbers. This last conclusion appears very clearly observing

Fig. 4(c) and (d), where liquid was introduced as jets. This arrangement provided higher fractions of liquid atomised, typically between 50 and 80% [24]. For this particular case it is quite likely that Yung et al. [2] equation would predict correctly the mechanism of drop acceleration, but neglecting the stress gas-wall leads to noticeable underestimation of the total pressure drop. It appears clear that the stress wall-gas, or gas-film, cannot be neglected in small-scale venturis.

The models of Azzopardi and coworkers [5–7] and Boll [4] are approximately equivalent in the case of jet injection as it can be observed on Fig. 4(c) and (d). Both models give satisfactory predictions in this case.

Fig. 5 illustrates the poor predictions of the equation proposed by Calvert [1] for small venturis. His equation ignores the stress wall-gas, assumes complete atomisation of liquid, and finally that all the drops are accelerated to the velocity of the gas. All of those hypotheses are not reasonable in this case. The same figure shows that the water injection arrangement is an important factor on pressure drop, ignored by the models of Calvert [1], Yung et al. [2] and Boll [4]. The model proposed by Boll [4] gives better estimations for the case of jet injection, while Yung et al. [2] produces values usually lower than those obtained using Boll's model [4].

5.2. Case 2: medium-scale cylindrical venturi scrubber

The experimental results from Yung et al. [2], obtained in a venturi of medium size, with water injected as jets are compared in Fig. 6 against the predictions of various models for two different throat lengths. The corresponding performance indexes for each model are listed on Table 3.

The model proposed by Calvert [1] overestimates pressure drop once again, as previously observed in the case of small-scale venturis. You can observe in Fig. 6(a) that for a longer throat the predictions from Calvert [1] are slightly better, but still not satisfactory. The model by Calvert [1] does not include any geometrical parameter in the equation. In any event, a longer throat means more length for the liquid to accelerate close to the velocity of the gas. In this condition the hypotheses of Calvert [1] are more likely to be true.

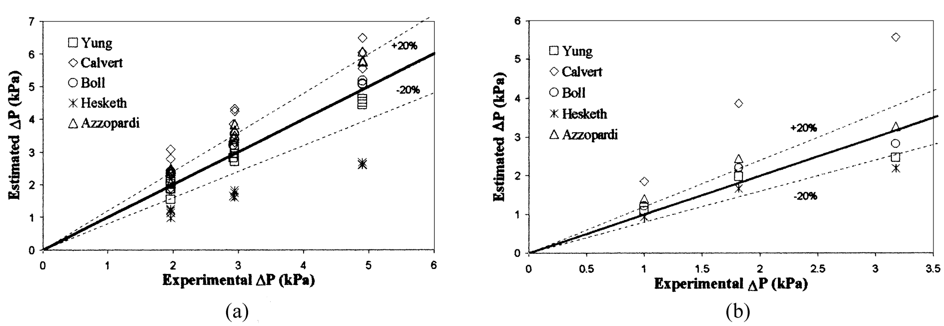

Fig. 6. Comparison of the predictions of models of Yung et al. [2], Calvert [1], Boll [4], Hesketh [3] and Azzopardi and coworkers [5–7] to experimental data of Yung et al. [2], for lengths of throat of 42.5 cm (a) and 12.1 cm (c).

Table 3
Deviation and tendency model performance indexes for the medium-scale cylindrical, pilot-scale and small scale rectangular venturi scrubbers

Model	Index	Medium-scale cylindrical longer throat	Medium-scale cylindrical shorter throat	Pilot-scale cylindrical	Small-scale rectangular
Boll [4]	Deviation	0.11	0.18	0.13	0.10
	Tendency	+0.10	+0.11	+0.02	−0.04
Yung et al. [2]	Deviation	0.07	0.14	0.14	0.61
	Tendency	−0.04	−0.01	+0.06	−0.61
Azzopardi and coworkers [5–7]	Deviation	0.21	0.26	0.25	0.11
	Tendency	+0.21	+0.26	+0.25	−0.07
Calvert [1]	Deviation	0.30	0.92	0.31	0.43
	Tendency	+0.29	+0.92	+0.29	−0.43
Hesketh [3]	Deviation	0.43	0.15	0.15	0.68
	Tendency	−0.43	−0.15	−0.12	−0.68

The empirical correlation proposed by Hesketh [3] gives reasonable predictions for the short throat (Fig. 6(b)), but it fails for the longer throat (Fig. 6(a)). It is a usual problem with empirical correlations the possibility of failure when extrapolated to conditions far from those where they were obtained.

The model proposed by Yung et al. [2] gives good predictions for both throat lengths. When the diameter of the venturi increases the mechanism of stress wall-gas becomes less important, and the results of Yung et al. [2] approximate those of Boll [4]. However, it must be noted that the equation proposed by Yung et al. [2] was validated using his own data, and it must not be surprising the good performance for this particular case.

Once again you can see that the model of Boll [4] and that of Azzopardi and coworkers [5–7] produce similar results, with a tendency of the model of Azzopardi and coworkers [5–7] to give slightly higher predictions. The difference between both models can be observed in Fig. 7. On that figure you can see the profile of pressure drop along the scrubber for these two models, for the venturi of Yung et al. [2] with the longer throat.

Boll [4] assumes complete atomisation of the liquid, while Azzopardi and coworkers [5–7] predict that 10% of the liquid will be flowing as a film in this particular case. As a result, only 90% of the liquid will be used in the calculations of pressure drop due to drop acceleration, compared to 100% for Boll's case [4]. Apart from this, it must be remarked that these models use different correlations for the estimation of drop size and drag coefficient on the drops. All these reasons explain why the curves in Fig. 7 begin to diverge at the entrance of the throat, where the liquid is injected. As a result, Boll [4] predicts higher pressure drop at the end of the throat. In the diffuser these two models differ considerably. Boll's model [4] allows for the total recovery of the kinetic energy of the gas, while Azzopardi and coworkers' model [6,7] considers the effects of the boundary layer in the diffuser and produces lower pressure recovery. At the end of the equipment Azzopardi and coworkers [5–7] predicts a total pressure drop slightly higher.

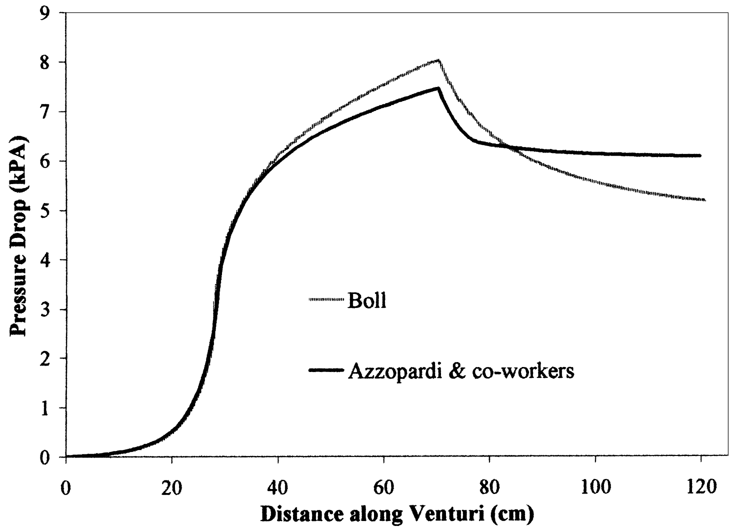

Fig. 7. Comparative example of pressure drop profile predicted by models of Boll [4] and Azzopardi and coworkers [5–7], venturi of Yung [2], with a length of throat of 42.5 cm.

The model of Azzopardi and coworkers [5–7] describes the flow in a more realistic way than the one proposed by Boll [4]. On the other hand, it relies on a number of semi-empirical equations and parameters in order to estimate the growth of the boundary layer [23], size and initial velocity of drops, fraction flowing as a film, among others.

5.3. Case 3: pilot-scale venturi scrubber

Fig. 8 shows the predictions of the models by Yung et al. [2], Calvert [1], Boll [4], Hesketh [3] and Azzopardi and coworkers [5–7] against the experimental data of Allen and Van Santen [19] for the case of a pilot-scale venturi. The performance indexes for each model are listed in Table 3.

As the diameter of the venturi increases, the mechanism of pressure drop due to drop acceleration becomes more predominant. Both in the case of jet injection and film injection the fraction of water flowing as a film is quite low, usually below 10% for a scrubber of this size.

Although the hypothesis of the equation of Calvert [1] are more likely to be true, it still overestimates pressure drop significantly, as it can be observed in Fig. 8. Even if the performance indexes for the model of Calvert are multiplied by the 0.85 factor, they will still be higher than those of Boll's model, for example. The model of Azzopardi and coworkers [5–7] also tends to overestimate slightly pressure drop, probably due to some of the reasons previously mentioned.

Hesketh [3] tends to underestimate the experimental data of Allen and Van Santen [19], but not as much as in the previous examples (Fig. 6(a)). The estimations of Boll [4] and Yung et al. [2] are spread around the line of perfect agreement. The non-inclusion of the stress wall-gas does not appear to be important in this case.

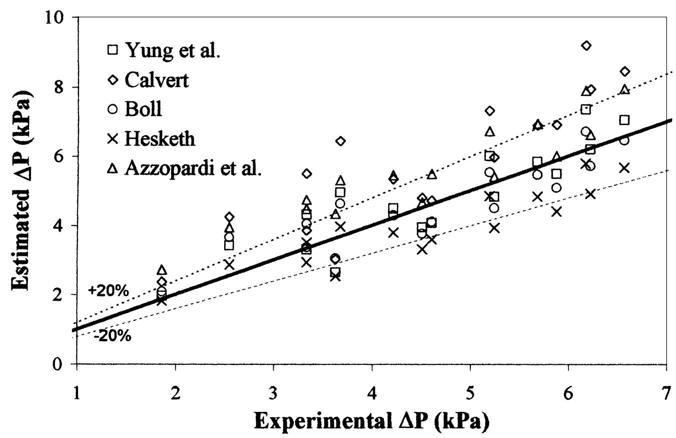

Fig. 8. Predictions of models against experimental data from Allen and Van Santen [19].

5.4. Case 4: small-scale rectangular venturi scrubber

Fig. 9 shows the performance of the models of Calvert [1], Yung et al. [2], Hesketh [3], Boll [4], Azzopardi and coworkers [5–7] in their capacity to predict the data reported by Gonçalves et al. [25] for a small rectangular venturi scrubber. The performance indexes for each model are listed on Table 3. The concept of HEV as described in the theory was used in order to make possible the application of the model of Azzopardi and coworkers to the rectangular geometry.

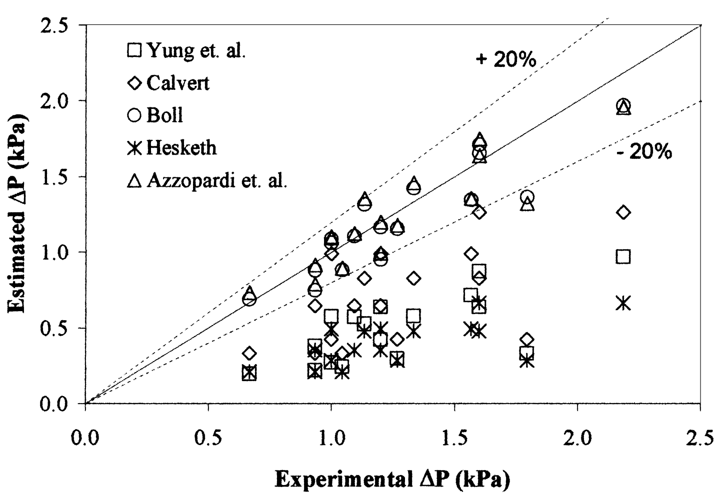

Fig. 9. Predictions of models against experimental data from Gonçalves et al. [25].

Besides the rectangular geometry, this venturi was characterised by its small size and low amount of liquid utilised. Under these conditions, friction is the most important mechanism for the total pressure loss of the equipment. Through the use of Boll's model [4] the contribution of the mechanism of friction to the pressure loss was estimated to be between 47 and 75% in all runs. The jet injection system made possible low film fractions, whereas the long throat lengths used in some runs allowed the drops to accelerate to final velocities not too far from the throat gas velocity.

The models of Calvert [1], Yung et al. [2] and Hesketh [3], which do not take friction into account, grossly underestimate the data (Fig. 9). The deviation indexes for these models ranged between 40 and 68%, which is of the order of magnitude of the relative importance of friction.

The models of Boll [4] and Azzopardi and coworkers [5–7] performed very well, with deviation indexes of the order of 10%. The predictions of these two models were very similar for this venturi. It was a surprise to see the good performance of the model of Azzopardi and coworkers [5–7] for the rectangular geometry. This indicates that the use of the HEV concept may allow the use of this model for a rectangular geometry. However, more studies are needed before final conclusions are drawn.

6. Conclusions

From this analysis it can be concluded:

1. The geometric characteristics of the equipment must be considered. An equation like the one proposed by Calvert [1], ignoring geometry, can lead to quite inaccurate predictions.
2. The fraction of liquid atomised is an important parameter to take into account. The fraction of water flowing as film depends on the liquid injection arrangement and the flow conditions. Only the model by Azzopardi and coworkers [5–7] provides an estimation of this parameter.
3. Empirical correlations are not valid for the whole range of operating conditions of practical interest.
4. The model of Azzopardi and coworkers [5–7] presents a tendency to overestimate slightly pressure drop in the cases studied here. This result suggests a revision of the methods the model uses for the estimation of the fraction atomised, drop size and the parameters involved in the calculations in the boundary layer growth [13].
5. The scale of the venturi influences the relative importance of the different mechanisms producing pressure drop.

For the engineer, in a practical case we suggest:

1. Not to use the equation by Calvert [1], unless an initial estimation of the order of magnitude of the pressure drop is necessary.
2. The model proposed by Yung et al. [2] fails seriously in the case of small venturis. Its performance improves as scale increases. Even in this last case, it shows a tendency to underestimate pressure drop. This tendency is potentially risky in a practical case, as it will predict a more optimistic scenario than the real situation, and it will be possible that the scrubber will not be able to achieve the conditions scoped in the design. For this reason we do not advise the use of this model.

3. If the fraction of liquid atomised is high (>75%), which should happen normally in venturi scrubbers of medium and higher scale with liquid introduced as jets, the model proposed by Boll [4] works satisfactorily. The numerical and computational effort required by the model of Azzopardi and coworkers [5–7] is not justified in these conditions.
4. When it is necessary a general model that would give acceptable results for cylindrical venturi scrubbers in all operational conditions and would rarely underestimate pressure drop it is necessary to use the model of Azzopardi and coworkers [5–7]. For rectangular venturi scrubbers the model can be used with caution, applying the HEV concept defined in this paper.

Nomenclature

A_t	area of the section of the throat (m^2)
C_{Da}	drag coefficient used by Yung
C_{drops}	concentration of drops (kg/m^3)
d_e	equivalent diameter in the model of Azzopardi and Govan, taking into account film thickness (m)
D_D	drop diameter (m)
D_e	equivalent diameter of the duct (m) D, Dt duct diameter (m)
f	friction factor used in the calculation of the shear stress gas/wall
F_{dep}	flux of deposition of liquid onto the film (kg/m^2 s)
F_{ent}	flux of liquid entrained from film (kg/m^2 s)
G	volumetric flow of gas (m^3/s)
$H_{D,i}$	volumetric fraction of drops of group i
H_G	volumetric fraction of gas
HEV	hydraulic equivalent venturi scrubber
K	constant of mass transfer in Eq. (11) (m/s)
L	volumetric flow of liquid (m^3/s)
m	mass ratio liquid/gas
P	pressure (Pa)
U_{Df}	velocity of drops at end of throat (m/s)
U_D	velocity of drops (m/s)
$U_{D,i}$	velocity of drops of group i (m/s)
U_{Gf}	velocity of gas at end of diffuser (m/s)
U_{Gt}	velocity of gas at throat (m/s)
U_G	velocity of gas (m/s)
W_f	mass flow of film (kg/s)
x	distance along axis of the venturi (m)
X	dimensionless parameter of throat

Greek letters

β	dimensionless parameter in Eq. (5)
ρ_G	density of gas (kg/m^3)
ρ_l	density of liquid (kg/m^3)
τ_w	shear stress at the interface gas/film (N/m^2)

Acknowledgements

J.A.S. Gonçalves, M.A. Martins Costa and J.R. Coury gratefully acknowledges the financial support from CNPq and Pronex-Finep.

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