VALIDATION OF A PROCEDURE FOR DIMENSIONING A CYCLONE SEPARATOR FOR CIRCULATING FLUIDIZED BED GASIFIER

De Paula A. C. O.*, Henríquez J. R. and Figueiredo F. A. B.
*Author for correspondence
Department of Energy,
Faculty of Mechanical Engineering
State University of Campinas,
Rua Mendeleyev, 200, Cidade Universitária “Zeferino Vaz”, 13083-860 - Campinas - SP
Brazil,
E-mail: ana.carolina@fem.unicamp.br

ABSTRACT

Circulating fluidized bed technology presents great particle mixing capacity. A cyclone separator is coupled to gasifier reactor and is responsible for particulate separation and producer gas cleanup. Cyclone dimensioning must be done carefully, according to the conditions this device is going to be submitted. Thus, this work aims to validate and analyze a dimensioning methodology and apply it to a gasifier. Three cyclone geometries were considered (Stairmend, Swift and Lapple) and are compared in terms of collection efficiency and pressure drop. At the end, a parameter sensibility study was also reported, thus variation of dimension, efficiency and pressure drop for a producer gas volumetric flow range was tested.

INTRODUCTION

Biomass has shown to be an excellent option for complementary energy generation, since this biofuel can be harnessed from residues in agricultural and industrial processes. One of the many conversion processes of biomass, gasification, produces a gas fuel (syngas) that can be used in gas turbines or internal combustion alternative engines. Several comparisons on conversion routes of biomass were made and gasification has shown to be a more favourable route than direct combustion [1]. Biomass is an ideal fuel for gasification for its high volatile content and high reactivity [2]. Gasification process, however, produces a great quantity of solid particles of different granulometry. In the circulating fluidized bed gasifier, the cyclone separator is incorporated in the gasifier and is responsible for the initial cleaning of the producer gas and circulation of particulate material that is carried by the gas back to the bed [3].

Most of efficiency prediction models for cyclone separators are empirical. One of the first models for collection efficiency related collection efficiency to the tangential velocity component of the gas in the cyclone vortices and the terminal settlement velocity of the particle [4]. Further development on separation efficiency prediction was made, and a study have presented an expression relating separation efficiency with cut-off diameter and particle diameter [5]. Cyclone efficiency was related to the size of the particles in the flow. Relations between the geometry of the cyclone and the collection efficiency were made [6]. It was found that the exit tube dimensions are related to cyclone efficiency. Large exit tubes results in not defined spirals, thus exit tube dimensions impares efficiency. Also, if all other dimensions are kept constant, larger cyclones have higher collection efficiency.

NOMENCLATURE

a	[m/s]	Entrance height
b	[m/s]	Entrance length (ft for Equation 3)
C	[-]	Dimensionless configuration parameter
D	[m]	Cylindrical section diameter (ft for Equation 3)
d_c	[m]	Diameter at the natural length
D_d	[m]	Diameter of the dust exit
d_{pi}	[mm]	Average ash diameter
D_x	[m]	Diameter of vortices tube
E_f	[-]	Collection efficiency
g	[m/s]	Gravity acceleration (ft/s^2 for Equation 4)
h	[m]	Height of the cylindrical section
H	[m]	Total height of the cyclone
l	[m]	Cyclone natural length
n	[-]	Tangential velocity parameter
P	[W]	Power
R	[m/s]	Project constant
S	[m]	Length of the vortice tube
T_g	[^{o}C]	Gas temperature at the exit of the reactor
$\dot{V}_g$	[m^3/s]	Volumetric flow rate of producer gas
V_e	[m/s]	Entrance velocity (ft/s for Equation 3)
V_s	[ft/s]	Saltation velocity
W	[ft/s]	Parameter for saltation velocity calculation
ΔP	[Pa]	Pressure drop
Special characters		
μ_g	[kg/ms]	Gas viscosity (lb/fts for Equation 4)
ρ_g	[kg/m^3]	Producer gas density (lb/ft^3 for Equation 4)
ρ_p	[kg/m^3]	Particles density (lb/ft^3 for Equation 4)
ρ_{g-p}	[kg/m^3]	Gas-particle flow density
ξ	[-]	Constant factor
φ	[-]	Modified parameter of inertia
Subscripts		
ex		Exhaustion

Most efficiency models involve force balance and some simplifications that eliminates some of the present terms. However, an incorrect simplification results in wrong dimensioning, thus dimensioning models must be chosen carefully according to the operation conditions that this device is subjected [7]. In general, the increase in separation efficiency is reached when the centrifugal effect is also increased. Many factors influence the pressure loss, such as geometry, rugosity, gas temperature operation, entrance velocity and solids load. One of the first models to determine pressure drop does not consider friction and vortices formation [8]. One of the most used models considers that particles are uniformly mixed and is limited to a restric range of body diameter [9].

Thus, aiming to study, dimension and assist on correct geometry choice, a dimensioning method was validated and applied. At the end to this work, a sensibility study was performed to present how cyclone dimensions and performance varies when gasifier parameters are changed.

ANALYSIS

For this work analysis, a fluidized bed gasifier found in the literature was considered for cyclone dimensioning [10]. Gasifier parameters for cyclone dimensioning and analysis are: producer gas flow rate, gas temperature, gas viscosity and density, particles density and diameter. Three cyclone types were considered: Stairmand (high efficiency), Swift (high efficiency) and Lapple (general purpose). The most common configuration for gas cleaning is the reverse flux with tangential entrance, thus this will be the designed geometry. The configuration of this cyclone is represented in Figure 1.

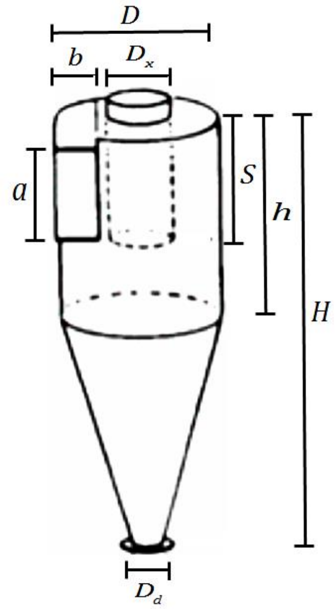

Figure 1 Cyclone separator in analysis

The entrance duct is placed in such a way that the gas is forced to enter the cyclone tangentially to the inner wall of this device. The circulating path of the flux yields centrifuge force to the particles, and they move in the direction of the wall. By gravitational force, these particles slide to the bottom of the spire. At the conical section, the flow is forced to the inner area of the separator and directed upwards [11].

The cyclone basic dimension is the diameter of cylindrical section:

$$D = \sqrt{\frac{\dot{V}_g}{R}} \tag{1}$$

The project constants R can be found on Table 1 [12]. The entrance velocity is obtained dividing the volumetric flow rate of generated gas by the area of the entrance nozzle:

$$V_e = \dot{V}_g \Big/ \left(a \cdot b\right) \tag{2}$$

Table 1 Gasifier data for cyclone dimensioning

Cyclone Family	R
Lapple (general purpose)	1.90556
Swift (high efficiency)	1.37222
Stairmand (high efficiency)	1.52778

The other dimensions of the cyclone are given by the multiplication of the factor *k* by the diameter of cylindrical section. These factors values are presented in Table 2.

Table 2 Geometric relations for some cyclone families

Geometry	k_a	k_b	k_{Dx}	k_S	k_h	k_H	k_{Dd}
Stairmand	0.5	0.2	0.5	0.5	1.5	4	0.37
Swift	0.44	0.21	0.4	0.5	1.4	3.9	0.4
Lapple	0.5	0.25	0.5	0.62	2	4	0.25

In order to obtain highest collection efficiencies, the gas velocity at the entrance must be as high as possible. The minimum velocity to ensure separation between solid particles and gas flow is named saltation velocity, and is given by [13]:

$$V_s = 2{,}055W \left[\frac{\left(\frac{b}{D}\right)^{0{,}4}}{\left(1-\frac{b}{D}\right)^{1/3}} \right] D^{0{,}067} V_e^{2/3} \tag{3}$$

The parameter *W* is defined by:

$$W = \left[\frac{4g\mu_g(\rho_p - \rho_g)}{3\rho_g^2} \right]^{1/3} \tag{4}$$

Collection efficiency is given by the following expression [9]:

$$E_f = \left[1 - exp\left(-2(C\varphi)^{1/(2n+2)}\right)\right] x100 \tag{5}$$

φ is a modified parameter of inertia, that meets particle information and gas properties. This parameter can be described by the following expression:

$$\varphi = \frac{\rho_p d_{pi} V_e (n+1)}{18\mu_g D} \tag{6}$$

The change in tangential velocity is given by the parameter *n* and can be calculated by [5]:

$$n = 1 - \left[\left(1 - 0{,}67 D^{0{,}14}\right) \left(\frac{T_g + 273{,}15}{283} \right)^{0{,}3} \right] \tag{7}$$

The geometric parameter C depends on the eight main dimensions of the cyclone. This parameter is obtained by the expression [9]:

$$C = \frac{\pi D^2}{ab} \{C_1 + C_2 + C_3\} \tag{8}$$

where C_1 represents the following term:

$$C_1 = 2\left[1 - \left(\frac{D_x}{D}\right)^2\right]\left[\frac{S}{D} - \frac{a}{2D}\right] \tag{9}$$

C_2 represents the following term:

$$C_2 = \frac{1}{3}\left(\frac{S - l - h}{D}\right)\left(1 + \frac{d_c}{D} + \frac{d_c^{\,2}}{D^2}\right) \tag{10}$$

C_3 represents the following term:

$$C_3 = \left(\frac{h}{D}\right) + \left[\left(\frac{D_x}{D}\right)^2 \left(\frac{l}{D}\right)\right] - \left(\frac{S}{D}\right) \tag{11}$$

The cyclone natural length can be calculated by the following expression:

$$l = 2{,}3 D_x \left(\frac{D^2}{ab}\right)^{1/3} \tag{12}$$

The diameter at the natural length is given by [9]:

$$d_c = D - \frac{(D - D_d)(S - l - h)}{H - h} \tag{13}$$

Another important parameter that qualifies the efficiency of a cyclone is pressure drop. This drop is given specially to the expansion of the gas as it enters the cyclone body. Friction and vortices formation are also cause of pressure drop, however these losses are much lower and are disregarded. From Bernoulli equation, pressure drop is calculated by [14]:

$$\Delta P = \xi \frac{\rho_{g-p} V_e^2}{2} \tag{14}$$

The constant factor ξ depends on the cyclone type and can be defined by:

$$\xi = 16 \frac{a\,b}{D_x^2} \tag{15}$$

The exhaust fan consumed power in order to maintain the volumetric flow constant is given by:

$$P_{ex} = \dot{V}_g \; \Delta P \tag{16}$$

Initial Conditions

Cyclone dimensioning and analysis requires information related to the gas that is being cleaned. This data is obtained of a gasifier found on the literature and is presented on Table 3.

Three cyclone types were considered for analysis: Stairmand (high efficiency), Swift (high efficiency) and Lapple. For sensibility study, producer gas flow rate is varied from 0.1m^3/s and 0.5m^3/s and the variation of dimensions, efficiency and pressure drop in the cyclone is analyzed.

Table 3 Gasifier data for cyclone dimensioning [10]

$\dot{V}_g$	T_g	μ_g	ρ_g	ρ_p	ρ_{g-p}	d_{pi}
0.224	850	4.09x10^{-5}	0.289	180	0.717	0.0296

DESIGN PROCEDURE AND PARAMETER ANALYSIS

The first step to dimension a cyclone is the decision of cyclone type according to project requirements. In this work, Stairmand, Swif and Lapple cyclones were chosen for analysis. After cyclone type decision, the basic project dimension must be calculated: diameter of cylindrical section. Total height of the cyclone, vortex diameter, length of the vortex tube, height and length of entrance, height of cylindrical section and diameter of exit tube of collected particles, are dependent to the diameter of cylindrical section and are calculated multiplying this quantity for the respective factor *k.*

After cyclone is dimensioned, efficiency is calculated. Cyclone efficiency and pressure drop are determined. Finally, the exhaustion gas engine power is calculated. Cyclone dimensioning steps can be found in Figure 2.

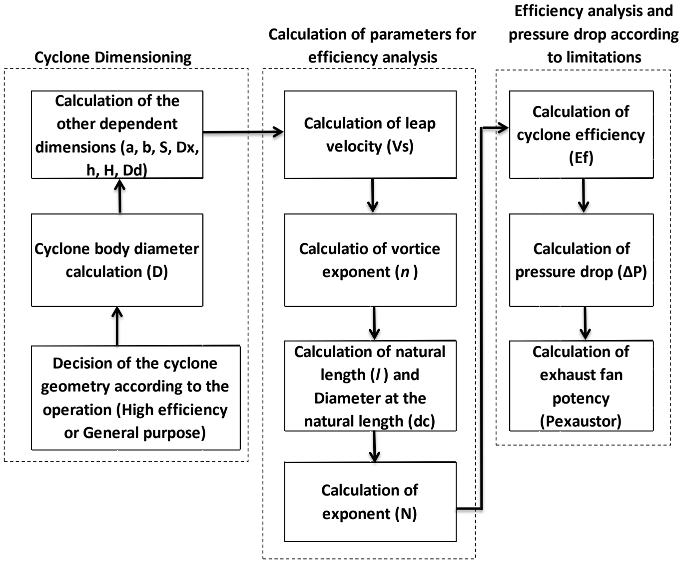

Figure 2 Steps for in cyclone separator dimensioning and performance determination

Independently of the cyclone type, the following configuration recommendations must be fulfilled [13]:

- $a \leq S$ to avoid dead short of particulate at the entrance section to the exit tube;
- $b \leq (D - D_x)/2$ to avoid excessive pressure drop;
- $H \geq 3D$ to maintain the vortice end inside the conical section of cyclone;
- $D_x/D \approx 0{,}4\text{-}0{,}5$, $H/D_x \approx 8\text{-}10$ e $s/D_x \approx 1$ to assure operation at maximum efficiency;

- Inclination angle of cyclone cone must be between 7 and 8° to assure fast dust sliding.

The last stage of this work is the parameter sensibility analysis. In the first analysis, volumetric flow rate of producer gas was varied between 0,1 and 0,5 m^3/s and variation of dimensions was studied. In the second analysis, dimension of the cyclones were kept fixed at the dimensioned values in the beginning of the section and volumetric flow rate was varied. Thus, cyclone efficiency and pressure drop was analyzed.

Validation of the method

The method presented in this work was validated comparing results to the ones presented in the literature [10]. The comparison was performed for Swift geometry. Results are shown in Table 4.

Table 4 Method validation

Parameter	Present work	Mendoza [10]
a (m)	0.178	0.166
b (m)	0.085	0.079
D (m)	0.404	0.378
D_x (m)	0.162	0.151
S (m)	0.202	0.189
h (m)	0.566	0.529
H (m)	1.576	1.473
D_d (m)	0.162	0.151
V_s (m/s)	17.0	18.46
E_f (%)	82.78%	84.86%

RESULTS AND DISCUSSION

The dimensioning procedure was done through the described procedure in Figure 2 for three cyclone types: Stairmand, Swif and Lapple. The calculated dimensions can be found on Table 5. From the three compared cyclone types, Stairmand cyclone presented the lowest separation efficiency (81.86%) and also the lowest pressure drop (535.5Pa). The separation efficiency from this cyclone was close to Lapple, however, the obtained pressure drop was considerably higher. The calculated entrance velocity (15.3m/s) was lower than the saltation velocity (16.9m/s), thus particles do not return to the gas flow and particles collection is not compromised. From the three studied cyclone type, Stairmend presented the highest natural length (0.949m). It also presents the lowest required exhaust power of all studied types.

Swift high efficiency cyclone presented the highest efficiency of the three studied types (82.78%). This separator presented the highest pressure drop (730.6Pa), thus the requirement of exhaustion power was also the highest (163.6W). Despite the low difference in separation efficiency, Swift cyclone presented a pressure drop 36% lower than Stairmand. In general, collection efficiency increases if pressure drop increases, however, the increase rate is not proportional when considering different cyclone types. Swift cyclone presented the lowest entrance velocity (14.8m/s), which is also bellow saltation velocity (16.9m/s).

Table 5 Gasifier data for cyclone dimensioning

Parameter	Stairmand	Swift	Lapple
a (m)	0,191	0,178	0,171
b (m)	0,077	0,085	0,343
D (m)	0,383	0,404	0,086
D_x (m)	0,191	0,162	0,171
S (m)	0,191	0,202	0,214
h (m)	0,574	0,566	0,686
H (m)	1,532	1,576	1,371
D_d (m)	0,144	0,162	0,086
l (m)	0,949	0,822	0,788
d_c (m)	0,241	0,294	0,224
V_e (m/s)	15,3	14,8	15,2
V_s (m/s)	16,8	17,0	18,6
E_f (%)	81,86%	82,78%	81,90%
ΔP (Pa)	535,5	730,6	666,5
P_{ex} (W)	119,9	163,6	149,3

Lapple cyclone presented the second highest collection efficiency (81.9%). Despite the difference in collection efficiency between Lapple and Stairmand is very small, Lapple cyclone presented pressure drop 24% higher than Stairmand.

Figures 3, 4 and 5 show the variation of cyclone dimensions for Stairmand, Swift and Lapple respectively for the gasifier considered. Figures indicate that, for the three mentioned cyclone, increase in volumetric flow rate results in a dimension increase. The cyclone total height (H) and cylindrical section height are the dimensions that mostly increase with flow rate.

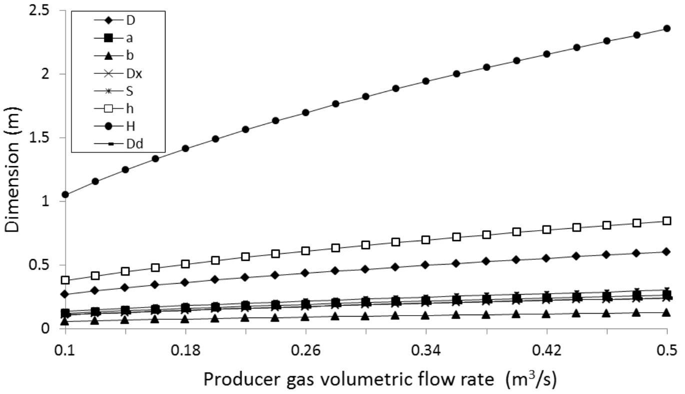

Figure 3 Dimensions variation and volumetric flow rate for the considered gasifier (Stairmand)

Figure 6 presents the variation of collection efficiency when volumetric flow rate of producer gas is increased (and cyclone dimensions are kept fixed). This figure indicates that the increase in the flow rate leads to an increase in collection efficiency. Figure 7 presents the variation of pressure drop when volumetric flow rate is increased (dimensions are kept fixed). This figure indicates that an increase in the flow rate also results in an increase in pressure drop. However, whereas collection efficiency increases uniformly, pressure drop increase depends on the cyclone type. Swift cyclone presents the highest pressure drop rates, and for high volumetric flow rates, the difference gap between Swift and Stairmand cyclone tend to be higher. Thus, cyclones are more sensible to variations in pressure drop when operating in high flow rates.

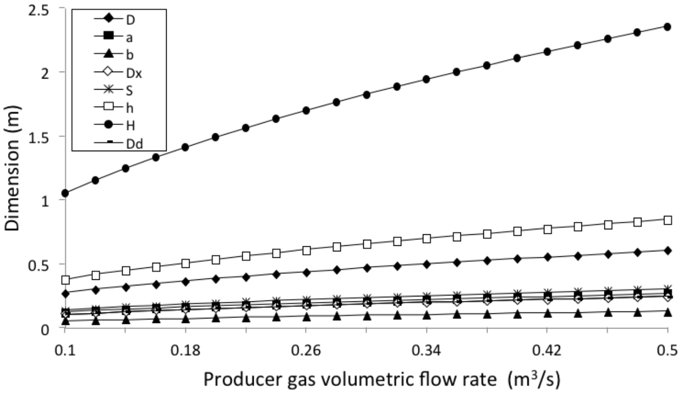

Figure 4 Dimensions variation and volumetric flow rate for the considered gasifier (Swift)

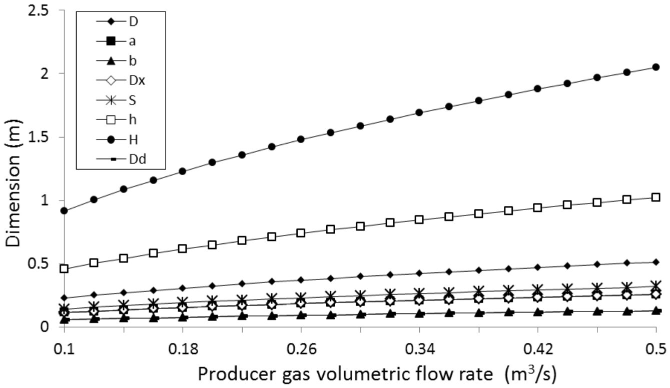

Figure 5 Dimensions variation with volumetric flow rate for the considered gasifier (Lapple)

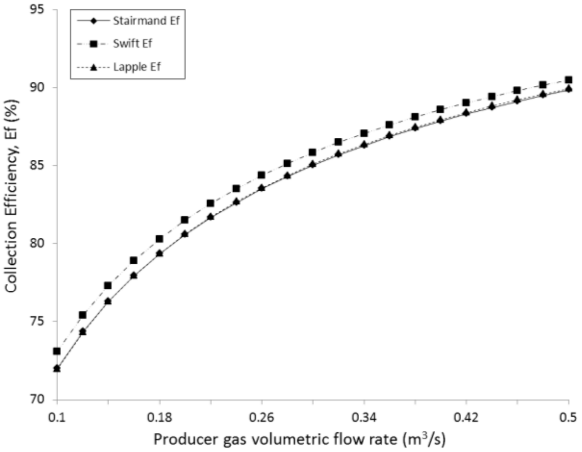

Figure 6 Variation of separation efficiency and volumetric flow rate for the considered gasifier

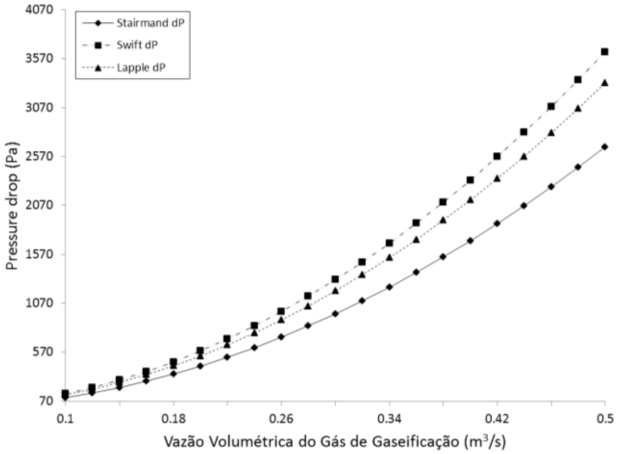

Figure 7 Variation of pressure drop with volumetric flow rate for the considered gasifier

CONCLUSION

The presented methodology was elaborated from equations and relations found on the literature and tested for a circulating fluidized gasifier. The required parameters for cyclone dimensioning were gas flow rate, gas temperature, viscosity and density of gas and particles. These parameters were also obtained from a gasification reactor found on the literature. The presented methodology of cyclone separator dimensioning was validated.

A cyclone separator was dimensioned and a parameter sensibility study was performed. Results indicate that, between the three studied cyclone types, the highest collection efficiency was reached by Swift. This cyclone presented the highest pressure drop and also the highest exhaustion power. The increase in gas flow rate produces an increase of separator dimensions. The most affected cyclone parameter to gas flow variation was the cyclone height. The parameter sensibility study have shown that pressure drop and collection efficiency do not increase in the same proportion when gas flow rate is varied.

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