Comprehensive Evaluation of Gas-Liquid Cyclonic Separation Technologies

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Abstract PDVSA-Intevep has developed a portfolio of technologies for gas–liquid phase separation based on centrifugal forces effects on fluids of different densities. Research has been focused on both separation technologies cylindrical–conical cyclonic (CYCINT®) and multiple cylindrical cyclones (CIMCI®), contemplating numerical modeling, construction, and extensive experimental tests conducted for a wide range of inflow rates and multiphase mixture properties (Brito et al. 2001, 2003, 2009; González et al. 2002; Martínez 2002; Carrasco 2008; Matson and Brito 2008; Cáliz et al. 2009; Valdez et al. 2009; Martínez 2010). Cyclonic separators are centrifugal technologies whose geometry construction promotes rotational flow within them. Centrifugal forces generated inside the separators conduct the fluid to follow a spiral trajectory with the heavier phase forced to flow nearby the separator walls, whilst the lighter phase is directed to the centre of the equipment ascending to the top of the device. This paper presents a comprehensive quantitative evaluation methodology based on a thorough parametric matrix developed to screen the most promising technologies based on experimental essays results. As a consequence, an optimal allocation of resources will allow further development of the top ranked technologies to conduct further field tests. The processing of experimental data from laboratory tests conducted on cyclonic technologies comprises parameters of great

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interest for the purpose of this evaluation. Gas carry under, liquid carry over, pressure loss, and generated G forces, in hand with liquid level control strategies, operational envelope width, operability, and compact design are some of the parameters used for the evaluation of technologies considered in this study. The evaluation of parameters was conducted through group categorization followed by variables grading on a 0–8 scale by means of a binary comparison methodology. The evaluation of technologies was conducted based on the results obtained during experimental tests and further analysis. As a result, an unbiased technology ranking was obtained, in which the multi-cylindrical technology (CIMCI®) provides an overall best performance with emphasis in a superior gas separation efficiency and easier constructability, whilst the cylindrical-conic cyclonic technology (CYCINT®), on the other hand, presented the upmost liquid separation efficiency and wider operational envelope. Further efforts will focus on continuous development of these two technologies to provide more compact, efficient, and economical gas–liquid separation solutions.

1 Methodology

Technology evaluation was conducted through a multiple binary decision method that reduces the subjectivity involved in decision making processes by providing binary parametric evaluation through matrix construction.The methodology assigns weight factors to the different parameters by means of a one-to-one comparison providing a matrix from which the proposed alternatives can be selected based on the highest scores obtained.

Experimental data processing from laboratory tests conducted on cyclonic technologies comprise the parameters shown in Fig. 1.

Further parametric evaluation was conducted through a two stages process: first a group categorization, and then variable grading, following the multiple binary decision methodology.

2 Cyclonic Technologies

CYCINT® cyclonic separation device is a vertical cylinder attached to a conical section. Its working principle is based on centrifugal forces that induce vortex formation, generated when the fluid enters the inlet nozzle, inducing a significant angular momentum that will not allow the heavier phase to turn as rapidly as the lighter phase, and then separating the liquid from the gas. Figures 2 and 3 present versions of the CYCINT® and CYCINT ER®, respectively.

The main difference between both devices is the inlet and gas regions geometry. CYCINT® inlet geometry emulates a 90° bend that allows the tangential entrance of the fluid to the conic section. The CYCINT ER®, on the other hand, incorporates a straight inlet in addition to a vortex finder at the top of the cylinder.

Fig. 1 Selected parameters for technology evaluation

CIMCI® separator is a device conformed by multiple cylinders; the inlet configuration is variable and depends on the type of flow: straight-through or reverse flow. Centrifugal forces generated within the separator force the fluid to flow following a spiral trajectory diminishing phase re-entrainment. Figures 4 and 5 show versions of the CIMCI® and CIMCI UP® whose main geometric difference is the inlet position located either in the middle section or the bottom of the cylinders for the CIMCI® and CIMCI UP®, respectively.

The paths of the fluid phases are different for both multiple cylindrical separators: within the CIMCI® the liquid attaches to the walls and descends to the bottom, meanwhile the gas near the walls follows a descending trajectory but as it migrates from the walls to the core zone, it reverses its flow direction following and ascending trajectory in the centre (reverse flow type), whilst in the CIMCI UP® the heavier phase is forced to ascend through the cylinder and leave the device through the annular space between the cylinder body and the vortex finder, meanwhile the gas also follows an ascending trajectory but leaves the device through the vortex finder (straight through type).

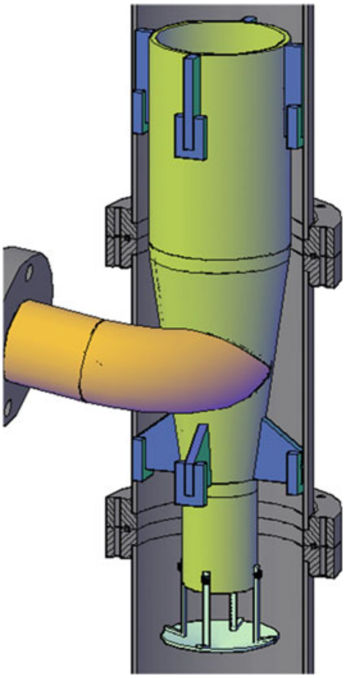


Fig. 2 CYCINT®

3 Technology Evaluation

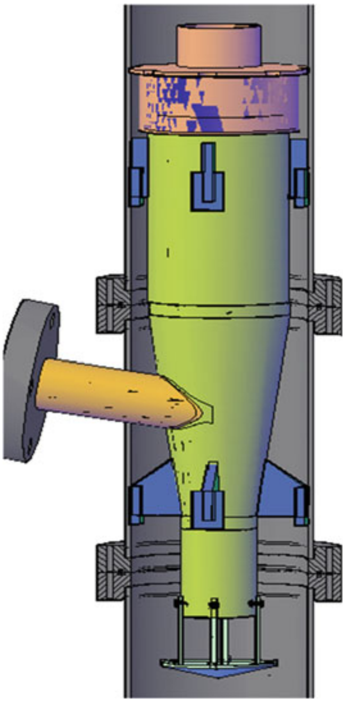
3.1 Experimental Results

Table 1 summarizes experimental test results conducted on the four cyclonic prototypes with two different two-phase mixtures (water-air and oil-air) at different inlet flow rates. The experimental measurements have focused on determining actual device operational envelope, gas carry under, liquid carry over, total pressure drop, tangential velocities, centrifugal forces, and predominating flow patterns. The experimental test results are shown in Table 1. Elements shaded in gray and blue represent the best and worst figures respectively for the given parameter.

3.2 General Matrix Weighting

Experimental data processing comprises not only direct measurements from laboratory tests but also parameters of great interest for the purpose of this evaluation. Following this, gas carry under (GCU), expressed as gas void fraction (GVF) in the liquid stream, liquid carry over (LCO) in the gas stream, pressure drop in the

Fig. 3 CYCINT ER®



separator, and generated centrifugal force, expressed as G forces, were considered for the technologies evaluation in hand with liquid level control, operational envelope width, operability, and compact design.

The evaluation of parameters was conducted through group categorization followed by variables grading on a 0–8 scale by means of a binary comparison methodology (we refer to Appendix A for details). On the other hand, technology evaluation was conducted based on the results obtained during experimental tests and further analysis, resulting in the technology weighting matrix shown in Table 2.

Based on the unbiased technology ranking obtained, a percentage distribution graph was constructed to better illustrate the technology ranking (see Fig. 6). Evaluation results show that the multi–cylindrical technology (CIMCI®) provides an overall best performance with emphasis in a superior gas separation efficiency and easier constructability, whilst the cylindrical–conical technology (CYCINT®), on the other hand, presented the upmost liquid separation efficiency and wider operational envelope.

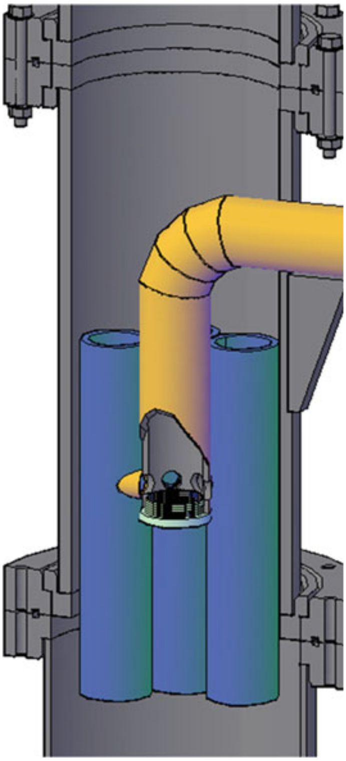


Fig. 4 CIMCI®

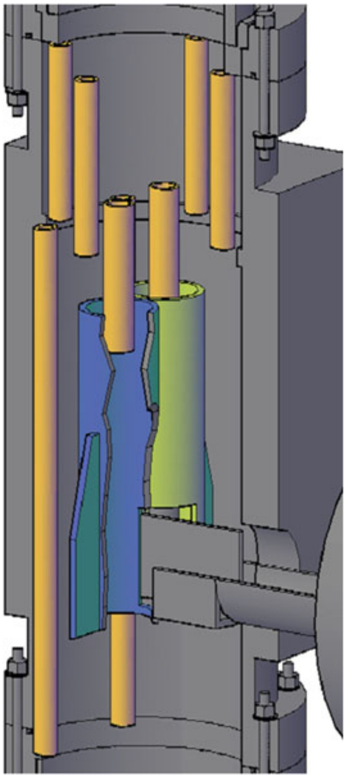
4 Analysis of the Parameters and Geometry Relations

A separation device classification was conducted based on the most representative geometric characteristics by region (inlet, gas, and liquid regions). From the analysis conducted here it was possible to identify the parameters whose magnitude was greatly influenced by the main geometric characteristics.

According to the results of the different experimental tests conducted with each cyclonic technology, it was observed a clear correlation between the devices geometry and their performance. Regarding the inlet area, there is a close relationship between the geometry of the devices and their performance when inlet operational conditions change; promotion of stratified flow in the inlet has been proven to contribute to the vortex formation and subsequent enhanced separation efficiency. Laboratory experiences also indicate that the use of a straight inlet for the CYCINT ER® combined with a vortex finder device results in a 40 % increase in gas handling capacity and lower gas carry under figures.

Similarly, the geometry of the gas region is closely related to the amount of liquid entrainment into the gas stream. After installing a vortex finder at the top of the cylindrical section of the CYCINT®, its latter version (CYCINT ER®) presented a

Fig. 5 CIMCI UP®



decrease in liquid carry over and better overall performance. Vortex finder installation, however, constricts the gas flowing area, promoting higher pressure drops.

5 Conclusions

The main conclusions can be summarized as follows:

- Multi-cylindrical technology (CIMCI®) provides an overall best performance.
- Multi-cylindrical technologies (CIMCI® and CIMCI UP®) provide superior gas separation efficiency than cylindrical–conical technologies.
- Multi-cylindrical technologies present significant advantages regarding adaptability, constructability, and compact design.
- Cylindrical—conical cyclonic technologies (CYCINT® and CYCINT ER®) present the best liquid separation efficiency and wider operational envelope.
- There is a clear correlation between the geometry of the devices and their performance.

Table 1 Experimental test results

MODEL	CYCINT®	CYCINT ER®		CIMCI®	CIMCI®	CIMCI UP®
Feeding Inlet	Inclined Tangential	Inclined Straight		Horizontal Tangential middle zone	Horizontal Tangential middle zone	Horizontal Tangential lower zone
Fluids	Water-Air	Water-Air Qg = 70	Oil-Air Qg = 26	Water-Air	Oil-Air	Water-Air
Operational envelope	Qg = 70	Ql = 706	Ql = 1500	Qg = 50	Qg < 50	Q = 50
	Ql = 1000	Qg = 50 Ql = 1200	Qg = 50 Ql = 91	Ql = 800	Ql = 800	Ql < 700
Gas void fraction	< 10 % @ Ql < 1000	10 % @ Ql < 1000	16 % @ Qg = 70 Ql = 1500	< 5 %	10 % Qg = 50 Ql = 800	< 5 %
Liquid carry over	Qg = 50.9 Ql = 1000	Qg > 50	Qg > 50 Ql = 500	Qg = 50 Ql = 1000	Qg = 50,9	Qg = 50 Ql = 500 > 5@ Ql = 700
Pressure drop	2 psi	4 psi	2 psi	< 5 psi	< 5 psi	< 5@ Ql = 500
Tangential velocity /	2–24 ft/s	2–24 ft/s	2.6–84 ft/s	8–37 ft/s	2.6–7.5 ft/s	7–130 G
G Force	0.9–10.5 G	0.9–10.5 G	1.1–49.9 G	5–22 G	1.1–3.2 G	
Flow pattern	Stratified	Stratified	Wavy stratified	Wavy stratified/slug	Wavy stratified/slug	

Qg: MSCFD
Ql: BPD

Table 2 Technology weighting results

Parameter		Weight	CYCINT®	CYCINT ER®	CIMCI®	CIMCI UP®
A	GVF	16.7	0.0	2.8	8.3	5.6
B	LCO	22.2	4.4	13.3	4.4	0.0
C	Pressure drop	11.1	5.6	3.7	1.9	0.0
D	Level control	19.4	0.0	3.2	9.7	6.5
E	Operational envelope	13.9	4.6	6.9	2.3	0.0
F	Constructability	5.6	0.0	0.9	2.8	1.9
G	Operability	0.0	0.0	0.0	0.0	0.0
H	Compact design	2.8	0.5	0.5	0.9	0.9
	Score	100	16	31	35	18

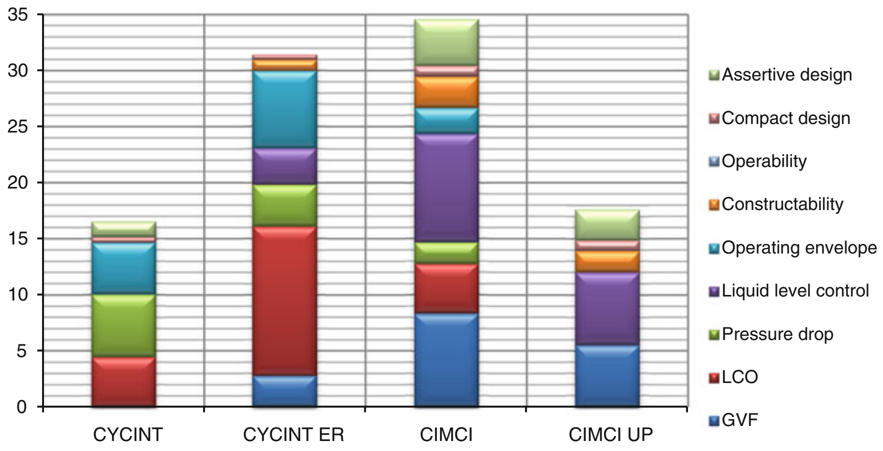


Fig. 6 Technology evaluation results

Table A.1 Parameters' comparison matrix (MBDM)

	A	B	C	D
A	–	0	1	1
B	1	–	1	0
C	0	0	–	1
D	0	1	0	–

Appendix A: Multiple Binary Decision Method

The binary comparison methodology employed for the technology evaluation is the Multiple Binary Decision Method (MBDM). The MBD method is used to assign weighting factors to different parameters comprised in an evaluation matrix and selecting, amongst different alternatives, the one that best qualifies according to the scores obtained. The procedure is detailed below and explained through a generic example:

(1) Selection of the more relevant parameters to be considered. These parameters should be precisely defined in order to quantitatively assess the alternatives under evaluation.
(2) Each selected parameter is assigned a weight resulting from a one-to-one comparison. This comparison determines which one of the evaluated parameters is the most important, by assigning it the value of '1' and the least important resulting with a '0' weight; following this procedure each parameter is compared to the remaining parameters. An illustration of the matrix obtained is shown in Table A.1.

Table A.2 Parameters' comparison matrix with weights (MBDM)

	A	B	C	D		SW	Weight (%)
A	–	0	1	1		2	33.3
B	1	–	1	0		2	33.3
C	0	0	–	1		1	16.6
D	0	1	0	–		1	16.6
					ST =	6	

Table A.3 Alternatives' comparison matrix for parameter A (MBDM)

	I	II	III		SW	Weight (%)
I	–	0	1		1	33.3
II	1	–	1		2	66.7
III	0	0	–		0	0.0
				ST =	3	

Table A.4 Alternatives' comparison matrix for parameter B (MBDM)

	I	II	III		SW	Weight (%)
I	–	0	1		1	33.3
II	1	–	1		2	66.7
III	0	0	–		0	0.0
				ST =	3	

(3) Once the one-to-one comparison is completed and the indicative 'ones' and 'zeros' are obtained, the parameter weighting factors are computed by applying the following equation:

$$weight = \frac{SW}{ST} \times 100, \quad \text{(A.1)}$$

where *SW* represents the weight of each parameter and *ST* is the total sum of the parameters' scores.

Table A.2 is complemented to illustrate the weighting distribution.

(4) Once the parameter weighting factors are obtained, the alternatives are evaluated. For the purpose of this illustration, three alternatives are proposed (I, II, and III). To obtain the most favourable alternative, all alternatives are compared to one another in reference to an alternate defined parameter. This way, alternatives I and II are compared to each other for parameter A, the alternative with the best performance gets a '1'; later alternatives II and III are compared and so on. Applying the weighting equation, the procedure is repeated, obtaining the alternatives' scores by parameter. Tables A.3, A.4, A.5 and A.6 illustrate the procedure.

Table A.5 Alternatives' comparison matrix for parameter C (MBDM)

	I	II	III		SW	Weight (%)
I	–	1	1		2	66.7
II	0	–	0		0	0.0
III	0	1	–		1	33.3
				ST =	3	

Table A.6 Alternatives' comparison matrix for parameter D (MBDM)

	I	II	III		SW	Weight (%)
I	–	1	1		2	66.7
II	0	–	0		0	0.0
III	0	1	–		1	33.3
				ST =	3	

Table A.7 Technology comparison general matrix (MBDM)

	Weight (%)	ALT. I (%)	ALT. II (%)	ALT. III (%)
Parameter A	33.3	(33.3 × 33.3) = 11.1	(66.7 × 33.3) = 22.2	(0 × 33.3) = 0
Parameter B	33.3	(33.3 × 33.3) = 11.1	(66.7 × 33.3) = 22.2	(0 × 33.3) = 0
Parameter C	16.6	(66.7 × 16.6) = 11.1	(0 × 16.6) = 0	(33.3 × 16.6) = 5.5
Parameter D	16.6	(66.7 × 16.6) = 11.1	(0 × 16.6) = 0	(33.3 × 16.6) = 5.5
Score	100.0	44.4	44.4	11.0

Following the previously described steps the alternative's partial score by parameter is obtained.

(5) Scores obtained in Tables A.3, A.4, A.5 and A.6 are then weighted by the specific weight computed for each parameter within the Parameters' Comparison Matrix (Table A.2). To exemplify this, take alternative II's weight for parameter A (66.7 %), parameter A weights 33.3 % according to Table A.2, thereafter alternative II score within the general matrix is computed as follows:

$$\frac{66.7 \times 33.3}{100} = 22.2\,\text{points.} \tag{A.2}$$

Scores obtained from Eq. (A.2) are later tabulated and added together to obtain the general score for every alternative. The alternative with the highest score will be the preferred one. Table A.7 illustrates the general matrix of technology selection.

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