Lobed jets for improving air diffusion performance in buildings

I. Nastase
Technical University of Construction in Bucharest, Building Services Department

A. Meslem
University of La Rochelle, LEPTIAB, France, ameslem@univ-lr.fr

ABSTRACT

A new innovative design concept for the indoor air conditioning systems is proposed. This concept uses passive control and modularly air diffusion devices and aims complying with both thermal comfort and energy efficiency objectives. Passive control aspect is studied through the comparison between a circular reference jet and a lobed jet having the same exit area and initial flow rate. It is shown that a cross-shaped lobed orifice allows a consequent increase of the entrainment within a large rage of initial Reynolds numbers. Moreover the jet's throw is conserved despite its strong initial induction. Streamwise volumetric flow rates and centreline velocities evolutions display an atypical region, in the range of the low Reynolds numbers, where commonly used prediction laws are not anymore valid.
Lobed jet's entrainment efficiency is elucidated through the analysis of the initial vortical structures dynamics.

1. INTRODUCTION

The primary aim of HVAC systems is to provide clean air and maintain comfortable conditions for occupants in buildings, both in terms of air quality and thermal comfort.

Energy consumption costs associated to these systems became a design criterion that cannot be ignored. Indeed, according to the European Commission's recommendations the EU members have to reduce their energy consumption within 20% before 2020.

The present study represents the preliminary stage of a new innovative design concept for the indoor air conditioning systems allowing both thermal comfort and energy efficiency objectives.

This concept represents a compromise between total-volume conventional air diffusion which is energy costly (Bin and Sekhar, 2007) and personalized air diffusion which is more efficient but yet susceptible to generate thermal discomfort (Sun et al. 2007). Our idea consists in using a modularly ceiling air diffusion device for the indoor air treatment of offices and industrial work places. The movable perforated panel on the ceiling allows the change of the air treatment zone which might be needed to follow an eventual displacement of the work-place within the room.

At this modularly device concept is added the idea of introducing passive flow control by using lobed cross-shaped perforation geometry instead of classical circular shape.

These innovative air diffusion terminal devices should allow a strong induction particularly in the initial region of the cold or hot air jet. The improved mixing will lead to a more stable flow, to the improvement of the thermal comfort and to the draught effects suppression.

These devices should also allow introducing the conditioned air at larger temperature differences and therefore a reduction of the volumetric flow rates resulting in supplementary energy savings and acoustical comfort amelioration.

Before the characterization of the innovative device performance we choose to preliminarily study the jet flow within isothermal conditions at the elementary orifice scale for different exit velocities in a range between 1m/s and 11m/s. This beforehand study is the object of the current article.

In a first place a detailed analysis of the studied flows is conducted for the lowest velocity value in order to evaluate the self induction power of the cross-shaped orifice in comparison to the circular reference orifice. An extension of this analysis is afterwards carried out for higher velocities. The mixing and induction performance of the lobed jet is next related to its vortical dynamics within the initial region in comparison with the reference circular jet.

2. EXPERIMENTAL SET-UP

The modularly ceiling air diffusion device concept that we suggest is schematized in Figure 1. Beyond the modular positioning of the air diffusion device that "follows" the work-place, a passive control method is also suggested. The method in question consist in using a cross-shaped geometry perforation (Figure 2 b) having the same effective area, A_{eff}, than the reference circular geometry perforation (Figure 2 a).

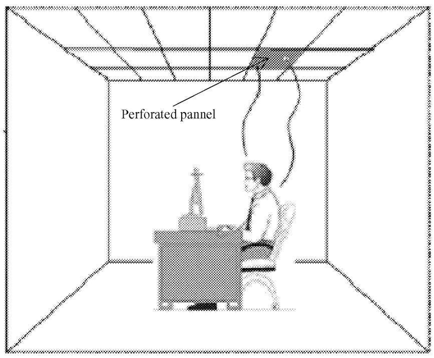

Figure 1: New concept of mixing modularly indoor air treatment

Considering the equivalent diameter $D_e = \sqrt{\frac{4}{\pi} A_{eff}}$ as a characteristic dimension, the Reynolds number takes values within a large range between 700 and 11000 (Table 1). The air jet facility used for the study of the elementary orifice jet is described in Figure 2 c.

A 2D-LDA system was used for the measurements of the mean velocity fields. A 2D-PIV system having a 15 Hz frequency acquisition was used for the measurement of the instantaneous velocity fields. The visualizations were performed using a 4W infrared laser and a high speed camera. The frequency could reach up to 5kHz for a 512x512 pixels² window.

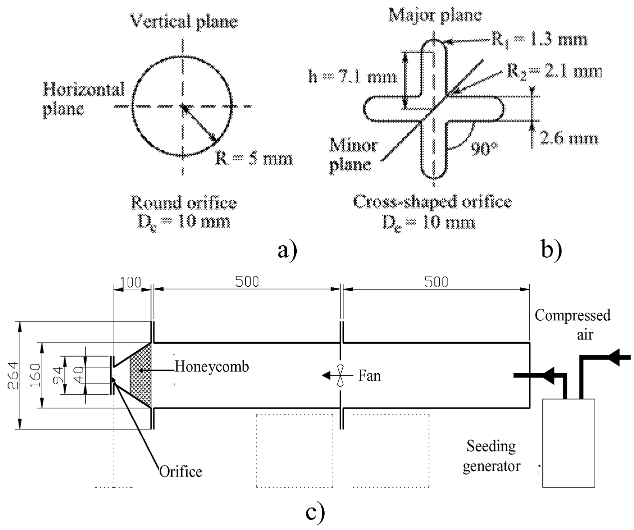

Figure 2: a) and b) Orifice's geometries, (c) Air jet facility sketch

Table 1: Exit conditions

A_{eff} (m²)	Q_0 (m³/s)	U_0 (m/s)	Re_0
78.5 x10^{-6}	7.87 x 10^{-05}	1.09	700
201.1 x10^{-6}	19.72 x 10^{-05}	0.98	1000
201.1 x10^{-6}	55.24 x 10^{-05}	2.74	2800
201.1 x10^{-6}	69.05 x 10^{-05}	3.43	3500
201.1 x10^{-6}	110.43 x 10^{-05}	5.49	5600
201.1 x10^{-6}	217.02 x 10^{-05}	10.79	11000

3. RESULTS AND DISCUSSION

In order to quantify the performance of the lobed cross-shaped orifice compared to the reference round orifice, the volumetric flow rates Q were evaluated based on the streamwise velocity U fields, at different axial positions X, up to X=15D_e. The stop criterion used for the flow rate integration deals with a streamwise velocity value chosen to be 0.2m/s. In Figure 3 we represented the streamwise evolution of the normalized volumetric flow rates $\frac{Q}{Q_0}$. In Figure 4 the corresponding normalized integration sections $\frac{A}{A_{eff}}$ are reported. This ratio quantifies the dynamical expansion of each jet. Figures 3 and 4 clearly display the larger induction and expansion of the lobed jet compared to the reference round jet.

In the air conditioning applications the criteria of self induction and expansion are not sufficient to characterise a jet flow. Indeed, a sufficient jet throw must be provided in order to reach the occupied zone. The strong dilution of the lobed jet may reduce its throw. This issue brought us to compare in Figure 5 the streamwise decays of the maximal velocities for the two jets (where U_{0m} is the exit centreline velocity). As displayed by this figure, the result is different than expected: the maximal values of the velocity decay faster in the round jet. This apparently contradictory result brought us to estimate the mean flow velocity by dividing the flow rate Q with the corresponding integration section A, based on the evolutions in Figures 3 and 4. The obtained results are presented in Figure 6. As expected, they show a faster decay of the mean flow velocity for the lobed jet. This result reveals another interesting characteristic of the lobed jet: its central region is relatively less mixed to the ambient air as its peripheral region.

It is shown by a large number of studies documented in the literature that the initial Reynolds number plays a major part in the jet flows behaviour, particularly in mixing and entrainment phenomena (Abramovich, 1963; Rajaratnam, 1976; Oosthuizen, 1983; Oosthuizen and Lemieux, 1985; Abdel-Rahman et al. 1996). In our case, the low velocity exit conditions results to an initial Reynolds number situated in an atypical behaviour range (Abdel-Rahman et al. 1996). This led us to verify whether if the observed entrainment efficiency is kept at higher Reynolds numbers usually found in HVAC applications for buildings and industry.

In Figure 7 a and b we represented respectively for the lobed and respectively the round orifice, the streamwise evolutions of the normalized volumetric flow rates $\frac{Q}{Q_0}$ within a range of the initial Reynolds numbers between 700 and 11000.

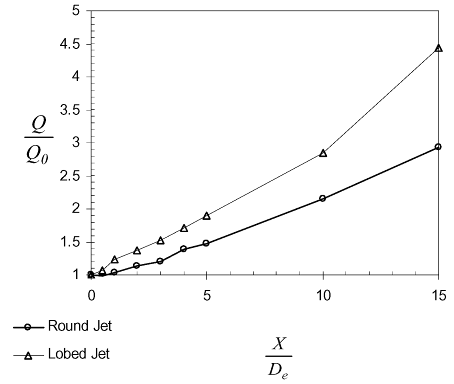

Figure 3: Streamwise variation of the volumetric flow rates for the two jets at Re_0=700

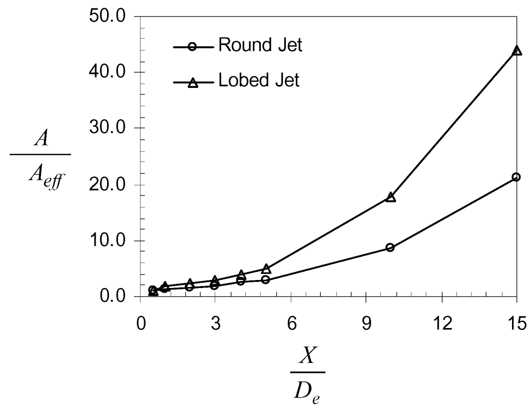

Figure 4: Streamwise variation of the flow area for the two jets at Re_0=700

The entrainment coefficient C and the corresponding virtual origin X_{01} of the evolution law $\frac{Q}{Q_0} = C\left(\frac{X + X_{01}}{D_e}\right)$ are given in Table 2 for each Reynolds number. Similar evolutions in function of the Reynolds number may be observed for both jets. For the circular jet it appears first an increase and next a decay of the normalized volumetric flow rates with the raise of the initial Reynolds number. A critical value of the Reynolds number is detected around 3500. In the lobed jet the critical Reynolds number is located around 2800.

Table 2 : Entrainment coefficients and virtual origins

	Round Jet			Lobed Jet		
Re_0	C	X_{01}/D_e	R^2	C	X_{01}/D_e	R^2
700	0.13	0.88	0.99	0.22	0.91	0.98
1000	0.38	1.07	0.99	0.47	1.32	0.98
2800	0.51	0.96	0.99	0.62	1.11	0.99
3500	0.57	0.93	0.99	0.59	0.68	0.99
5600	0.45	1.10	0.99	0.51	1.19	0.98
11000	0.35	0.89	0.95	0.43	0.94	0.97

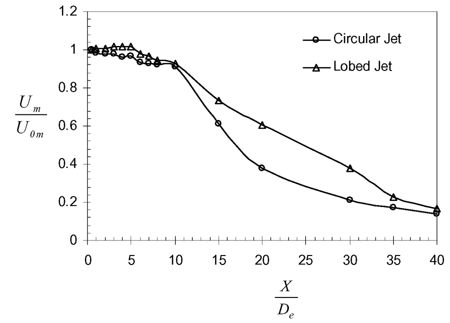

Figure 5: Streamwise variation of the centreline velocity for the two jets at Re_0=700

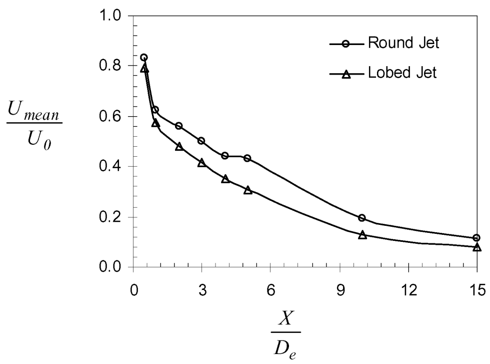

Figure 6: Streamwise variation of the mean velocity for the two jets at Re_0=700

The evolutions of the normalized flow rates with the initial Reynolds numbers are given in Figure 8 a and b at the axial positions X=10D_e and X=15D_e. In these figures we reported measurements by Ricou and Spalding (1960) for a circular jet at X=14D_e and X=25D_e. The recorded evolution for X=25D_e displays two distinct regions: the first one with a positive slope and the second one with a negative slope. Between them a critical point is situated around Re_0=3000. This comparison strengthens our results.

As for the critical point, it was found to be situated in a relatively narrow region. Considering the classification proposed by Abdel-Rahman et al. (1996), this region would correspond to the transition from an atypical flow regime to the turbulent stage.

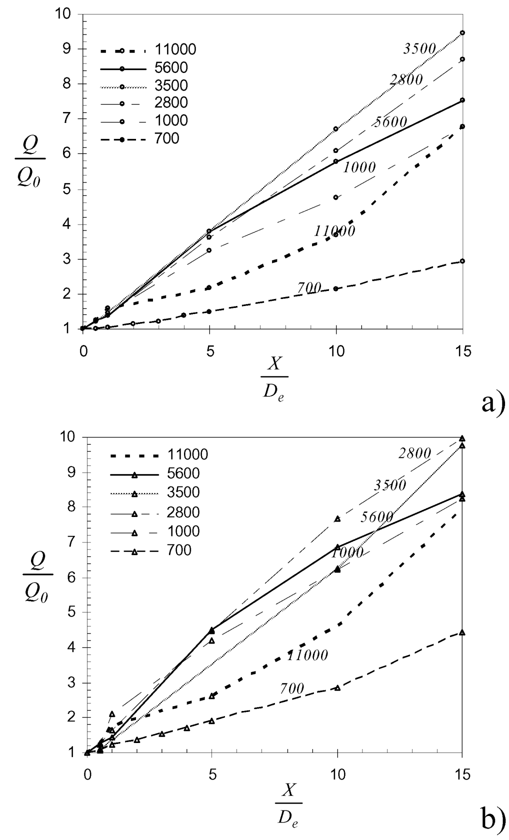

Figure 7 : Streamwise variation of the normalized volumetric flow rates with the initial Reynolds number : a) round jet, b) lobed jet

As suggested by these authors, the transition occurs around a Reynolds numbers of 2000. In our case a critical Reynolds number range, between 2000 and 3500, should be considered. The connection between jet's entrainment and flow regime's transition, that we are hereby proposing, was not evoked by Ricou and Spalding (1961).

As for the centreline velocity $\frac{U_m}{U_{0m}}$ evolution with the initial Reynolds number, we are taking over the comparison between our results and the documented literature for circular or plane jets in Figure 9 (Nottage, 1951; Oosthuizen and Lemieux, 1985; Malmström et al. 1997; O'Neill et al. 2004).This comparison was conducted at an axial distance of X=15D_e.

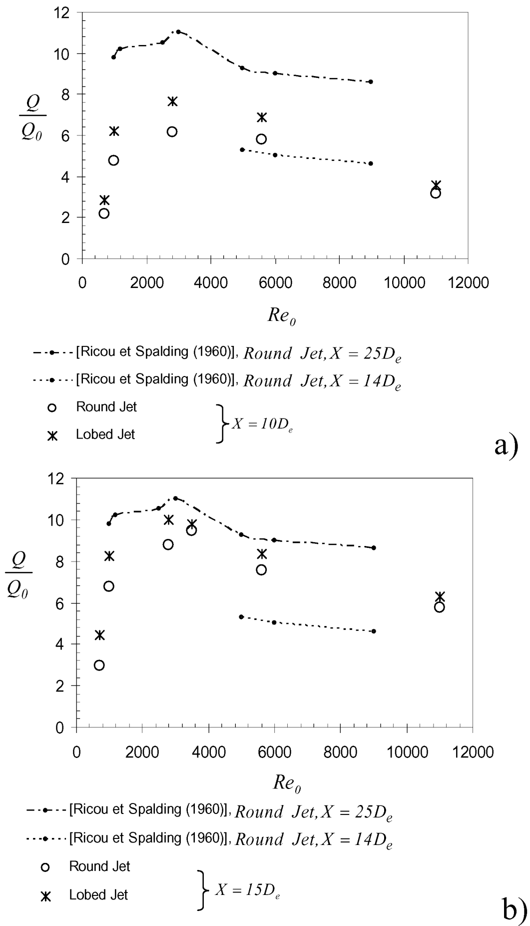

Figure 8 : Normalized volumetric flow rates variation with the Reynolds number. Comparison with the literature

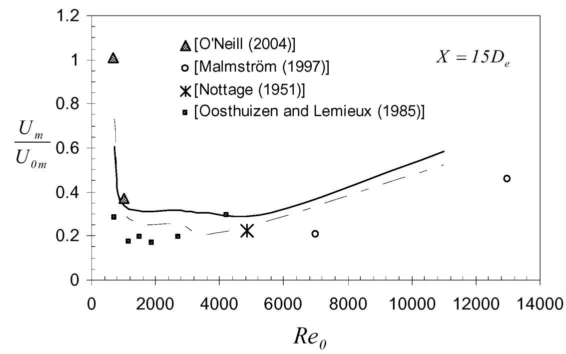

Figure 9: Normalized centreline velocities variation with the Reynolds number. Comparison with the literature

The results shown in Figure 9 put in evidence a critical range of low Reynolds numbers where the centreline velocity decay occurs slower. The classical K_V centreline velocity decay coefficient for an axisymmetric jet $\frac{U_m}{U_{0m}} = K_V \left(\frac{X + X_{02}}{D_e} \right)^{0.5}$, having generally a value around 6 (Rajaratnam, 1976), is obviously not anymore valid for this range. A more detailed analysis in order to establish the evolution low $K_V(Re_0)$ is needed.

In order to elucidate the phenomena governing the mixing performance of the lobed jet relatively to the round reference jet, a vortical structure dynamics analysis was conducted. This analysis combined two complementary investigation techniques: classical PIV and time resolved visualization enriched by low level image processing for contour detection in different observation planes. The employed procedure described in (Nastase et al. 2008). allows reconstructing pseudo-time resolved velocity fields for both jets. This way, it is shown that the lobed jet presents an important and particular dynamics being at the origin of its entrainment performance.

On one hand, as displayed in Figure 10, the primary structures of Kelvin-Helmholtz (K-H) are detaching at a fundamental frequency twice as higher in the lobed jet than in the circular jet.

On the other hand, these primary structures are discontinuous at the orifice's troughs, allowing at these points the development of streamwise secondary structures, which in their turn are well known for their self-induction role (Liepmann and Gharib, 1992; Suprayan and Fiedler, 1994; Hu et al. 2000; Hu et al. 2002).

In the circular jet the detaching of the continuous K-H rings opposes to the free development of the streamwise structures. The latter born between two consecutive K-H rings. As the K-H ring passes, the streamwise structures are compressed and their self-induction role is interrupted (Nastase et al. 2008). This analysis allows a better comprehension of the physical phenomena being at the origin of the high mixing performance of the lobed jet.

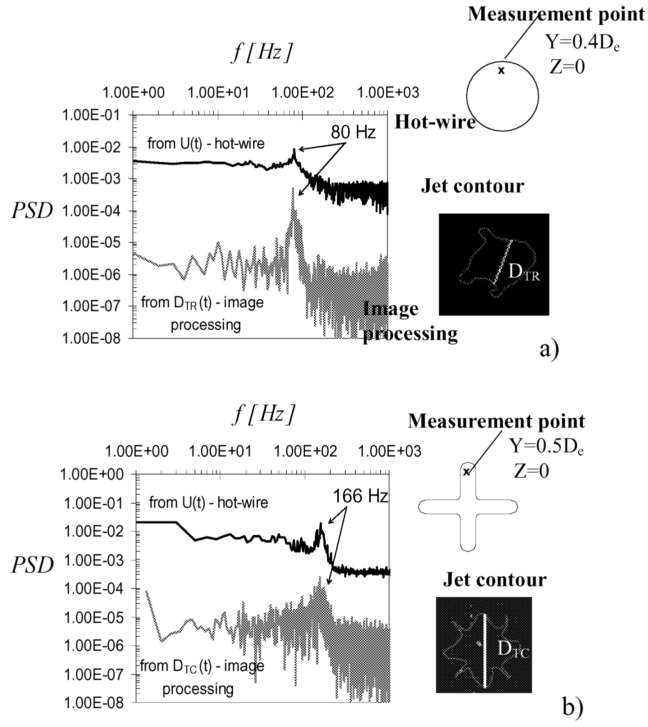

Figure 9: Comparison between the spectra of the streamwise velocity and of the jet dimension at $X=1D_e$: a) Round jet, b) Lobed

4. CONCLUSIONS

The idea of passive control of the jet flows for air conditioning was introduced trough the study of a lobed jet behaviour compared to a reference circular jet.

The mixing performance of the lobed jet was demonstrated within an initial Reynolds number range covering enough the conditions of the aimed application. It is shown that self induction occurs mainly in the jet periphery which is leading to a jet throw comparable to the one of the circular reference jet at same exit conditions.

It is also shown that the conventional behaviour prediction laws for jets in air conditioning are not adapted for flows at very low Reynolds numbers.

Beyond the global characterisation of the lobed jet compared to the reference circular jet, the analysis of the vortical dynamics in the near exit region explains the differences in mixing performance.

REFERENCES

Abdel-Rahman, A. A., S. F. Al-Fahed, et al. (1996),The near field characteristics of circular jets at low Reynolds numbers, Mechanics research Communications 23(3): 313-324.

Abramovich, G. N. (1963), (MIT) *The theory of turbulent jets,* MIT Press., Cambridge, Massachusets.

Bin, Y. and S. C. Sekhar (2007), Three-dimensional numerical simulation of a hybrid fresh air and recirculated air diffuser for decoupled ventilation strategy, Building and environment: 1975-1982.

Hu, H., T. Saga, et al. (2000). Passive control on jet mixing flows by using vortex generators. Proceedings of the Sixth Triennial International Syposium on Fluid Control, Measurement and Visualisation, Sherbrooke, Canada.

Hu, H., T. Saga, et al. (2002).,Mixing Process in a Lobed Jet Flow, AIAA Journal 40(7): 1339-1345.

Liepmann, D. and M. Gharib (1992). The role of streamwise vorticty in the near field entrainement of round jets, Journal of Fluid Mechanics 245: 642-668.

Malmström, T. G., A. T. Kirkpatrick, et al. (1997). Centerline velocity decay measurements in low-velocity axisymmetric jets, Journal of Fluid Mechanics 246: 363-377.

Nastase, I., A. Meslem, et al. (2008),Primary and secondary vortical structures contribution in the entrainement of low Reynolds number jet flows, Experiments in Fluids 44(6): 1027-1033.

Nottage, H. B. (1951). Report on ventilation jets in room air distribution. Cleveland, Ohio, Case Institute of Technology.

O'Neill, P., J. Soria, et al. (2004), The stability of low Reynolds number round jets, Experiments in Fluids 36: 473-483.

Oosthuizen, P. H. (1983), An experimental study of low Reynolds number turbulent circular jet flow, ASME Applied Mechanics, Bioengineering and Fluids Engineering Conference, Houston, U.S.A.

Oosthuizen, P. H. and G. P. Lemieux (1985), Experimental study of the behaviour of plane turbulent jets at low reynolds number, AIAA Journal 23(12): 1845-1846.

Rajaratnam, N. (Elsevier) (1976), *Turbulent jets*, Elsevier Scientific Publishing Company: Amsterdam.

Ricou, F. P. and D. B. Spalding (1960), Measurements of entrainement by axisymmetrical turbulent jets, Journal of Fluid Mechanics 11: 21-32.

Sun, W., K. W. Tham, et al. (2007), Thermal performance of a personalized ventilation air terminal device at two different turbulence intensities, Building and environment 42: 3974-3983.

Suprayan, R. and H. E. Fiedler (1994), On streamwise vortical structures in the near-field of axisymmetric shear layers, Meccanica 29(4): 403-410.