EXPERIMENTAL MODELS FOR THE DETERMINATION OF THE LENGTH OF THE ADJACENT ZONE FOR DISPLACEMENT VENTILATION DIFFUSERS

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ABSTRACT

Displacement ventilation (DV) systems have been widely used in Europe in the last decades. Compared to traditional mixing ventilation, DV systems provide a better indoor air quality and lower the cooling energy consumption by taking advantage of temperature stratification. However, a complaint generally associated with this kind of ventilation system is the draft discomfort it can induce. A common method to evaluate the risk of draft from a DV diffuser is to determine the Length of the Adjacent draft Zone (LAZ), i.e. the length of the zone where the maximal velocity is higher than 0.2 m/s. LAZ is currently listed by manufacturers' catalogues based on costly experimental measurements performed in environmental chambers. No mathematical model, neither theoretical nor experimental, exists to link the LAZ with supply characteristics. A few theoretical velocity decay models could be used, but would require experimentally determined coefficients, which are in turn more difficult to assess than the LAZ itself.

In this paper, the authors present two correlation models based on experimental data obtained from a manufacturer of DV diffusers. Seven types of wall displacement ventilation diffusers, each one of various sizes, are studied under different supply conditions. Two correlations models are then developed for the LAZ.

The first model developed by the authors agrees very well with experimental data for all the diffusers studied. The model uses three experimental coefficients for each diffuser. The advantage of the model compared to velocity decay models is that the coefficients used are independent of the supply conditions. In addition, two of the three coefficients are independent of the diffuser's size. The number of experiments required to determine the LAZ of a diffuser with various sizes and under various supply conditions is therefore significantly lowered. The second part of this paper presents an improvement of the correlation model. The second model requires three coefficients for each diffuser, all independent of the diffuser's size and of supply characteristics. The second model performs well when compared to experimental data for five of the seven diffusers studied, for all supply conditions and sizes.

This paper presents two correlation models for the LAZ of wall DV diffusers. The presented models accurately evaluate the LAZ of the diffuser studied, for various sizes and supply conditions, while minimizing the number of coefficients required.

INTRODUCTION

Displacement ventilation (DV) is an air distribution method that has been used for cooling in Northern Europe since the 1970s. In displacement ventilation, cold air is supplied at low velocity at floor level, typically through wall diffusers. The occupants then act as a plume source, and the air rises to the ceiling. Due to this air distribution, temperature stratification appears inside the room, which enables the cooling load to be decreased, while maintaining an acceptable thermal comfort. In addition, the supply air temperature in DV systems is generally higher than the supply temperature used for mixing ventilation systems. This higher supply temperature enables both energy savings, and a more frequent use of outside-air free-cooling. Finally, a better air quality is obtained, since occupants are supplied with fresh air rather than mixed air.

Despite these qualities, displacement ventilation is still used less often than traditional mixing ventilation. One of the reasons explaining the reluctance of designers to use DV is the risk of draft discomfort, caused by an excessive air velocity at foot level, which may appear if the DV system is not properly designed. Indeed, a recent survey of 227 workers in 10 office buildings equipped with DV showed that as much as 24% of occupants experienced discomfort at the lower leg level [1]. On the other hand, existing design tools for DV do not include the draft issue [2], and only a few tools are available for designers to assess draft discomfort. According to ASHRAE [3], the air velocity in the occupied zone should not exceed 0.2 m/s in order to avoid significant draft discomfort. Accordingly, in displacement ventilation, the zone where the velocity is higher than 0.2 m/s is called the adjacent draft zone. Knowing the extent of this zone is crucial for designers, in order to avoid discomfort.

Literature review

In the literature, the Length of the Adjacent Zone (LAZ) is in most cases listed in the manufacturers' catalogues. In order to create these catalogues, intensive experiments need to be performed in an environmental chamber for all the conditions and diffusers of interest, which is a very costly and time consuming process. No model, either theoretical or experimental, exists to directly relate the LAZ of a diffuser under different supply conditions. The only result that can be found in the literature regarding the LAZ is a relationship found by Skåret stating that, for a constant Archimedes number, the LAZ is linearly related to the flow rate to the 0.7 power [2]. While promising, this relationship offers little help for practical use, due to its limitation to a constant Archimedes number. In addition, the original study leading to this relationship is not accessible, and has only been published in Norwegian.

An indirect way to evaluate the LAZ is to use velocity decay models. The most widely used velocity model is Nielsen's model [4], based on the use of an experimentally determined constant K_{dr}:

$$\frac{v_x}{v_f} = K_{dr}\,\frac{H}{x} \qquad \textit{Equation 1}$$

where

- v_x is the maximum horizontal velocity at a distance x from the diffuser [m/s];
- v_f is the face velocity of the diffuser [m/s];
- K_{dr} is a constant independent of x [-];
- H is the height of the diffuser [m], and;
- x is the distance from the diffuser [m].

The LAZ can then be deduced using:

$$LAZ = K_{dr}\,\frac{H \cdot 0.2\ m/s}{v_f} \qquad \textit{Equation 2}$$

Nielsen's model is used as the reference model in major design guidelines such as the REHVA's guidebook [2] and ASHRAE's design guidelines [5]. This model has shown good agreement with experimental data [5,6], once the K_{dr} constant is properly determined. A major drawback of the model, however, is that the constant K_{dr} is dependent on the diffuser's type, on the diffuser's geometry (length and height), on the supply flow rate, and on the supply under-temperature. In other words, K_{dr} is valid only for a specific diffuser, with a specific size, and at specific supply conditions. Several studies tried to relate K_{dr} with flow characteristics [4,7], but no satisfactory result could be found. Therefore the constant has to be experimentally determined for all the diffuser's types and sizes and for all the under-temperatures of interest, through extensive and costly laboratory measurements.

Recently, Nordtest [8] proposed another velocity model for DV diffusers based on mathematical correlations. This model overcomes many shortcomings of Nielsen's model in that the coefficients used are independent of supply conditions. The coefficients are also independent of the diffuser size for a given aspect ratio. However, the model requires three experimentally determined coefficients for each diffuser. It also remains dependent on the height of the diffuser. Finally, the model has not yet been validated by an independent source. Overall, while promising, the model proposed by Nordtest requires further investigation, and still uses a relatively high number of correlation coefficients for a given type of diffuser.

As a conclusion, the velocity models used to find the LAZ of a diffuser, although efficient, generally require the use of numerous correlation coefficients. This is particularly true for the widely used Nielsen's model, which is dependent of both the diffuser geometry and the supply conditions. Nordtest model is in turn promising, but not fully validated. From a methodology standpoint, having to determine the whole velocity field to deduce the LAZ also appears both unnecessary and a source of error. A direct model to determine the length of the adjacent zone, with parameters independent of supply conditions and of the diffuser geometry, is to be found.

Methodology and experimental data

Although previous work focuses on determining the equation of the horizontal velocity decay, such information might not be necessary from a design point of view. In most situations, the length of the adjacent zone is the only parameter of interest for designers. The whole problem of characterizing the flow coming from a displacement ventilation diffuser can therefore be limited to the characterization of the adjacent zone. The approach retained for this paper is hence to find a model to correlate directly the LAZ with diffuser's and supply air characteristics. In order to develop this model, the authors used experimental data regarding the LAZ of various wall-diffusers (other types of diffusers and especially UFAD diffusers are outside the scope of this study).

The data used in this study is taken from experimental measurements performed in environmental chamber by [9]. The protocol used to measure the LAZ was based on Nordtest NT VVS-083 (first version) [10], which is a standard dedicated to the rating of low-velocity DV devices. No attempt is made here to describe the complete protocol and the reader is referred to the original study and standard for details. In a nutshell, for each diffuser type and each diffuser size, the LAZ was measured in steady-state conditions in a sufficiently large room, with uniformly distributed heat sources, at a minimum of four face velocities (0.1 m/s, 0.15 m/s, 0.20 m/s, 0.25 m/s), and two under-temperatures (2.8°C and 5.6°C). It should be highlighted that, although Nordtest standard uses a draft limit of 0.25 m/s, the usual definition of the LAZ with a velocity of 0.20 m/s was used. It should also be noted that the LAZ was measured at a constant height of 0.025 m from the floor.

This paper studies seven types of diffusers, summarized in Table 1. These diffusers cover a wide range of flat wall diffusers, including side-discharge and corners diffusers. All diffusers are studied for a minimum of seven sizes. For one type of diffuser (DF1R), two installations are studied (recessed and mounted), to see the effect of installation on the LAZ. Overall, a total of 76 different diffusers (types and sizes) are studied.

Table 1: Description of the diffusers studied

Diffuser	Type
DF1	Flat wall diffuser
DF1W	Flat wall-mounted diffuser
DF1WSS	Flat wall-mounted diffuser
DF3	Side-discharge flat wall diffuser
DF1R (recessed and riser mounts)	Flat large wall diffuser
DF1C	Flat corner diffuser
DR90	Quarter-cylinder corner diffuser

First correlation model

Studies of the plot of the LAZ versus the face velocity for various diffusers reveal a strong correlation between the LAZ and the face velocity (see Figure 2). In addition to the relation between the LAZ and the face velocity, one can also note that the impact of under-temperature increase, i.e. the difference in LAZ between under-temperatures of 2.8°C and 5.6°C, seems to be independent of the face velocity. This difference also seems constant for a given type of diffuser, regardless of its dimensions. Based on these findings and on regression analyses, the authors propose a general formulation for the length of the adjacent zone:

$$LAZ = C_D \cdot {u_f}^{0.7} + L_{\Delta T} + c_L$$

Equation 3

where:

- C_D is a coefficient independent of the air velocity or under-temperature [s];
- $L_{\Delta T}$ is a coefficient function independent of the face velocity and of the diffuser size [m], and;
- c_L is a coefficient independent of supply conditions, but specific to the diffuser size [m].

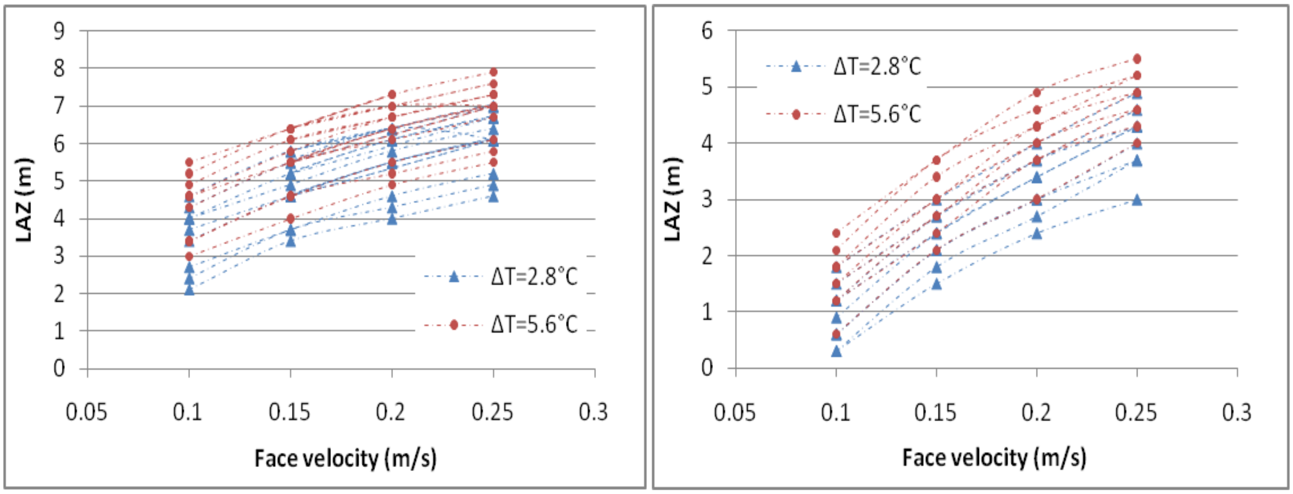

Figure 1: LAZ versus face velocity for all sizes of respectively DF1 and DF1R (riser mount)

The Equation 3 is divided into three parts. The first part accounts for the variation of the LAZ caused by the variation of flow rate. The coefficient C_D is a constant for a given diffuser, independent of its dimensions. The exponent chosen (0.7) is based both on regression analyses and on Skåret's early model. The second part of the equation accounts for the variation of LAZ caused by the variations of under-temperature, when changing the under-temperature from 2.8°C to 5.6°C. According to the experimental data, the coefficient $L_{\Delta T}$ is constant for a given type of diffuser, regardless of its dimension and regardless of the face velocity. Finally, the last part of the equation, c_L , is a coefficient specific to a given diffuser with a given size, but independent of the supply characteristics (flow rate and under-temperature).

The significant advantage of the proposed model, compared to the use of velocity decay models, is the independency of the three parameters used regarding supply conditions, and the independency of C_D and $L_{\Delta T}$ regarding the diffuser size. Thanks to this, a relatively small number of experimental measurements are required when testing a diffuser with several sizes and for several supply conditions. As an illustration, the experimental data regarding DF1C is based on 15 diffuser sizes, each one tested with 4 faces velocities and 2 under-temperatures. Using Nielsen's model to correlate the LAZ would therefore require the use of 120 different K_{dr} coefficients. Nordtest's model, in turn, would use 36 coefficients for the same purpose (3 coefficients for each of the 12 diffuser aspects ratios). Meanwhile, the correlation model proposed in this study only uses 17 coefficients (2 coefficients specific to the diffuser type, and 15 coefficients specific to the diffuser size), while keeping a very good accuracy. Thanks to the lower requirement for experimental coefficients, fewer measurements are necessary for the manufacturer to evaluate the LAZ of a diffuser.

The correlation coefficients found in this study are summarized in Table 2. The C_D coefficient for each type of diffuser is calculated as the average, for all the sizes of this diffuser, of the slopes between $u_f^{0.7}$ and LAZ at a given under-temperature. Similarly $L_{\Delta T}$ is calculated as the average, for all the sizes of a given diffuser, of the difference between the LAZ obtained with a given face velocity for an under-temperature of 2.8°C and the LAZ obtained at the same face velocity for an under-temperature of 5.6°C. The range taken by the c_L coefficients, specific to each size of a given type of diffuser, is also indicated.

Table 2: Correlation parameters for all diffusers

Diffuser type	C_D [s]	$L_{\Delta T}$ Increase in adjacent zone length between under-temperatures of 2.8°C and 5.6°C [m]	c_L range [m]
DF1	13.59	0.82	[-0.44, 2.02]
DF1W	23.79	-0.05	[-4.99, -1.99]
DF1WSS	24.63	-0.09	[-4.29, -2.24]
DF3	2.98	1.11	[0.63, 2.58]
DF1R (riser)	17.82	0.70	[-3.4, -1.78]
DF1R (recessed)	8.52	0.81	[0.39, 1.19]
DF1C	10.48	0.52	[-0.01, 1.99]
DR90	8.36	0.32	[-1.09, 1.31]

It is interesting to note that great variations appear for different types of diffusers for the coefficient C_D, as well as for the $L_{\Delta T}$ increase from an under-temperature of 2.8°C to an under-temperature of 5.6 °C. For instance, doubling the under-temperature increases the length of the adjacent zone by 0.8 m for DF1, whereas it has almost no effect on the length of the adjacent zone for DF1W and DF1WSS diffusers. For the DF1W and DF1WSS diffusers, the $L_{\Delta T}$ coefficient can indeed be considered as null, meaning that the change in under-temperature has no impact on the LAZ for the under-temperatures studied. For DF3 diffuser, in turn, the length of the adjacent zone increases by only 0.05 m if the face velocity is increased from 0.1 m/s to 0.25 m/s.

From a design standpoint, the proposed model enables the development of new guidelines regarding which diffuser to choose for specific operations, and how to operate a specific type of diffuser under different heat loads in order to minimize the length of the adjacent zone. In variable air volume systems with a constant under-temperature for instance, DF3 and DR90 should be chosen since an increase in flow rate only induces a limited increase in the LAZ for those diffusers. If a system is in turn designed to have a constant flow rate and a varying supply temperature, diffusers DF1W and DF1WSS would be very suitable, since the LAZ is barely affected by changes in under-temperature. Finally, as can be seen for the DF1R diffuser, the installation of the diffuser also has a significant impact on the LAZ, which shows that not only the diffuser *per se* affects the LAZ, but also its surrounding.

In order to study the accuracy of the model, the correlated LAZ have been compared with measured LAZ. Figure 2a plots the correlated LAZ versus the measured one for all the sizes of DF1 diffuser, for all supply conditions (face velocity and under-temperature) studied. The correlated LAZs have been obtained by using for each diffuser the C_D and $L_{\Delta T}$ coefficients specific to DF1 (defined in Table 2), and the c_L coefficient specific to the diffuser's size. The same process has been used to calculate the LAZ for the other types of diffusers studied. Results are illustrated in Figure 2. The R^2 values between the measured and correlation LAZ are summarized in Table 3. As can be seen, a very good agreement is found between correlated and measured LAZ, with R^2 coefficients always higher than 0.97. The developed correlation model is thus very accurate for all the diffusers studied, for all supply conditions studied.

Table 3: R-squared values for regressions using the first model

Diffuser type	R^2	Diffuser type	R^2
DF1	0.98	DF1R (riser)	0.99
DF1W	0.99	DF1R (recessed)	0.98
DF1WSS	0.99	DF1C	0.99
DF3	0.99	DR90	0.97

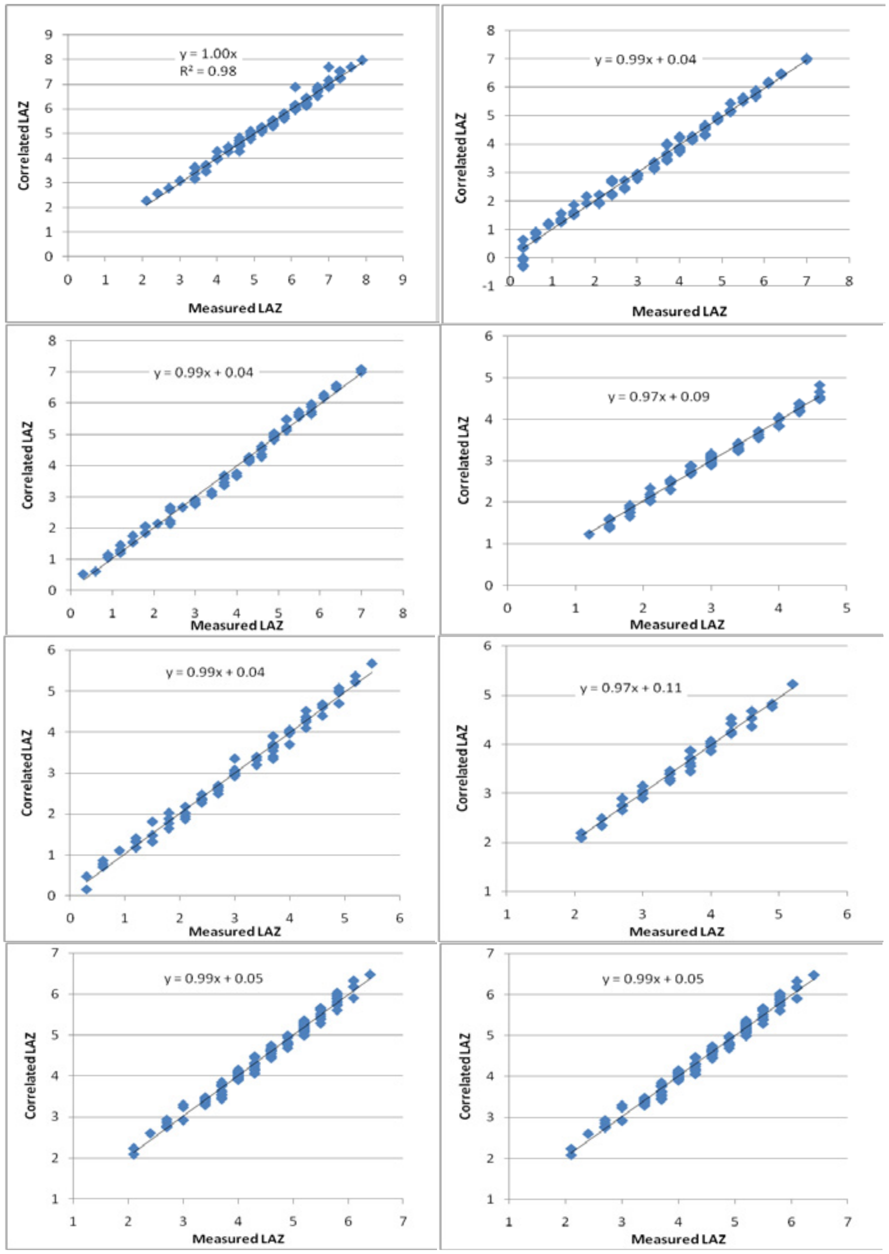

Figure 2: Measured Versus correlated LAZ for DF1 (a), DF1W (b), DF1WSS (c), DF3 (d), DF1R (riser (e) and recessed (f)), DF1C (g) and DR90 (h) (left to right, top to bottom)

Second correlation model

In the first model presented in this paper, the c_L coefficient is dependent on the diffuser size. For five of the seven diffusers studied though, c_L appears to be linked linearly with the hydraulic diameter of the diffuser (taken as the square root of the product of a diffuser's horizontal perimeter by its height). This relation is described in Equation 4, and illustrated in Figure 3 where the c_L coefficients are plotted versus the corresponding hydraulic diameter for all sizes studied of DF1W and DF1C diffusers.

$$c_L = k_1 \cdot \sqrt{H * W_p} + L_D$$

Equation 4

where:

- k_1 is a coefficient specific to the diffuser [-];
- H is the height of the diffuser [m];
- W_p is the horizontal perimeter of the diffuser [m], and;
- L_D is a coefficient independent of the size of the diffuser [m].

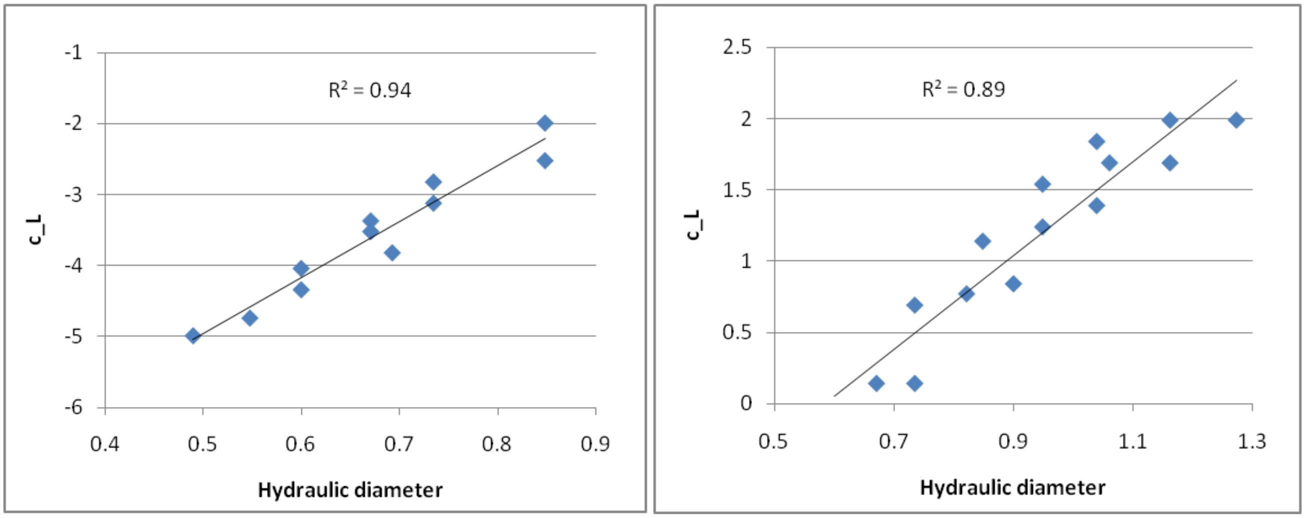

Figure 3(a,b): c_L coefficient against hydraulic diameter for DF1W and DF1C diffusers

In addition, further analysis shows that the k_1 coefficient used in Equation 4 can be taken as proportional to the C_D coefficient. This relation is summarized in Equation 5 and illustrated in Figure 4. Replacing equations 4 and 5 into Equation 3, the LAZ can be written as Equation 6. Using Equation 6, only three parameters (C_D, $L_{\Delta T}$, L_D), independent of the diffuser size, and independent of supply conditions, are required for each type of diffuser.

$$k_1 = 0.32 \cdot C_D$$

Equation 5

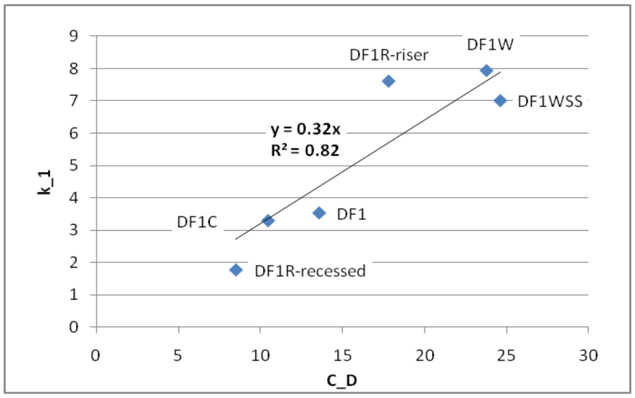

Figure 4: k_1 versus C_D coefficients for the diffusers studied

$$LAZ = C_D \cdot \left({u_f}^{0.7} + 0.32 \cdot \sqrt{H * W_p}\,\right) + L_{\Delta T} + L_D$$

Equation 6

It should be noted that Equation 6 is valid only for DF1, DF1W, DF1WSS, DF1R (both recessed and riser), and DF1C diffusers. This second correlation model is not applicable to DF3 diffuser, due to its particular side-discharge behavior, or to DR90, probably due to the inability to properly describe the hydraulic diameter. The correlation coefficients for the five types of diffusers are summarized in Table 4. Also presented in this table are the R^2 coefficients found when comparing the measured LAZ with the LAZ correlated using these coefficients. As can be seen, a good agreement is found between measured correlated data, with R^2 higher than 0.89 in all cases. Figure 5 plots the correlated LAZ versus the measured LAZ for the diffuser studied.

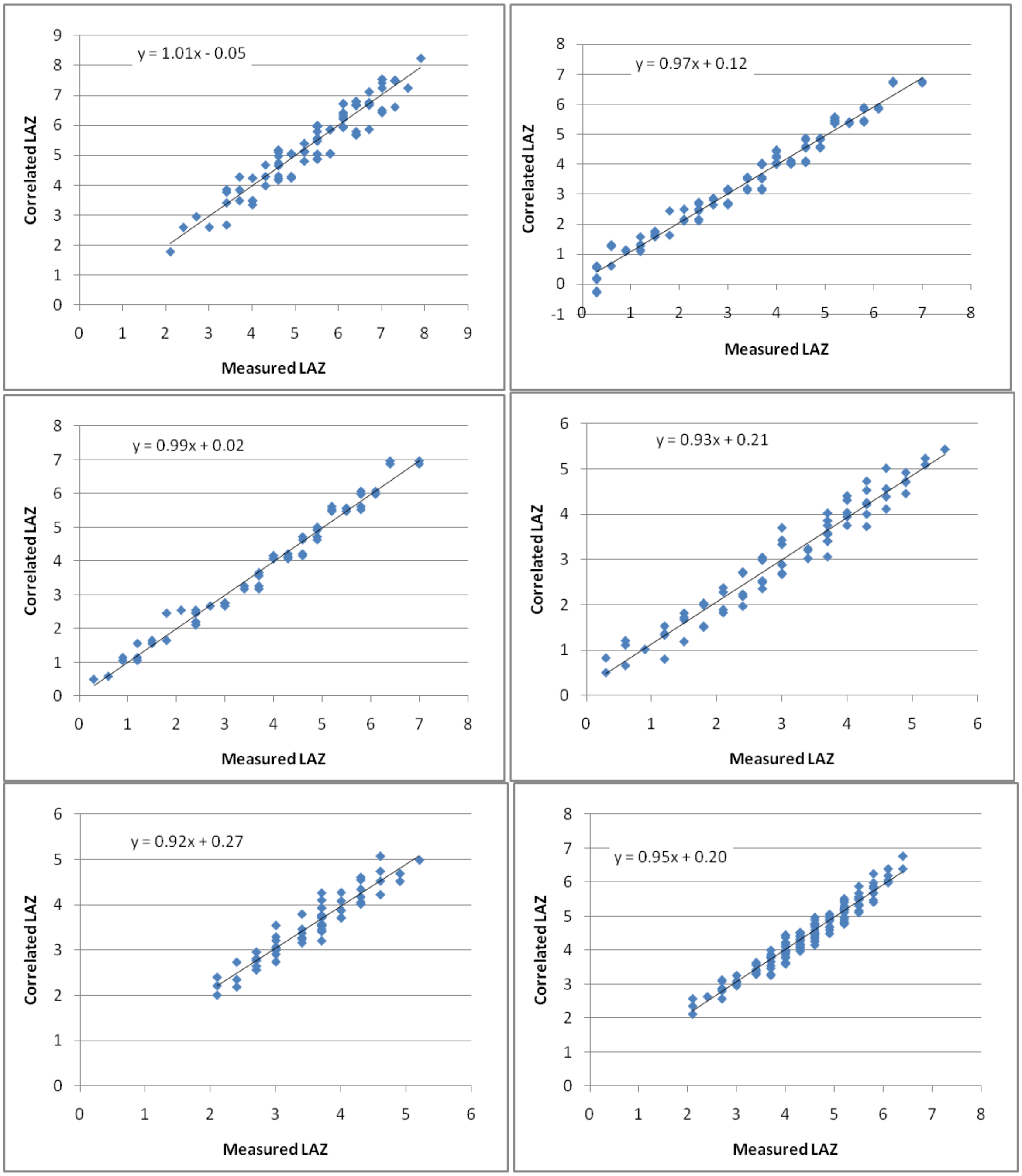

Figure 5: Measured versus correlated LAZ for DF1, DF1W, DF1R (recessed), and DF1C diffusers (left to right, top to bottom)

Table 4: Correlation coefficients of the second model

Diffuser type	C_D	$L_{\Delta T}$	L_D	R^2
DF1	13.59	0.82	-4.72	0.90
DF1W	23.79	-0.05	-8.72	0.97
DF1WSS	24.63	-0.09	-9.05	0.98
DF1R (riser)	2.98	0.70	-5.47	0.94
DF1R (recessed)	17.82	0.81	-1.46	0.89
DF1C	8.52	0.52	-1.98	0.95

Using the second correlation model, the LAZ can be determined using only 3 parameters independent of the flow rate, independent of the under-temperature, and most notably independent of the diffuser size, for each type of diffuser. For instance, the proposed model requires only 3 coefficients to determine the LAZ of DF1C with a fairly good accuracy. For the same purpose, Nielsen's model would require 120 coefficients and Nordtest's model would require 36 coefficients. The proposed model is therefore a major improvement for the evaluation of the LAZ, compared to the method based on velocity models. In addition, since the 3 parameters used are independent of the diffuser size, it is theoretically possible to only measure the LAZ for one size of a given type of diffuser, and then use the values for any sizes of this diffuser. The number of experimental measurements performed to assess the LAZ of a given type of diffuser with various dimensions and under various conditions is hence drastically reduced. The model is even applicable for situations where the diffuser size has to be customized to fit client needs.

Conclusion, limitations, and future work

The current paper proposes two correlation models to determine the length of the adjacent zone of various diffusers, under various supply conditions. The first correlation model enables the LAZ of all studied diffusers to be determined with a very good accuracy, using three coefficients for each diffuser. These three coefficients are independent of the supply conditions (for the conditions studied), and two coefficients are independent of the diffuser size. The second model presented in this paper correlates the LAZ with a rather good accuracy for five of the seven diffusers studied. This model uses three coefficients, all independent of the supply conditions and of the diffuser size. These two models significantly reduce the number of experimental coefficients to use when assessing the LAZ of a diffuser with different sizes and under different supply conditions, compared to the methods using velocity models. In terms of measurements, the proposed models also reduce the number of experiments required to be performed by DV manufacturers, and hence can save a significant amount of time and money.

While promising, the correlation models proposed in this article should be improved regarding the influence of the supply under-temperature. In this study, only two under-temperatures (2.8°C and 5.6°C) have been studied, due to the limitations of the experimental data. Future work should include different under-temperatures, in order to improve the models regarding the $L_{\Delta T}$ coefficient. Also, in the base experimental data used in this study [9], the maximal velocity was measured at a constant height of 25 mm from the floor. The maximal velocity might however not always happen at that height [4,11], and this may have caused some experimental inaccuracies.

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