A study of the atmospheric dispersion of an elevated release with plume rise in a rural environment: comparison between field SF_6 measurements and computations of Gaussian models (Briggs, Doury and ADMS 4.1)

C. Leroy[1], F. Derkx[2], O. Connan[1], P. Roupsard[1], D. Maro[1], D. Hébert[1] & M. Rozet[1]

[1]*Laboratoire de Radioécologie de Cherbourg-Octeville, IRSN/DEI/SECRE, France*

[2]*Veolia Environnement Recherche et Innovation, Département Environnement et Santé, France*

Abstract

In order to reduce uncertainties and enhance the knowledge of elevated releases atmospheric dispersion in a rural plain, the French Institute for Radioprotection and Nuclear Safety (IRSN), in collaboration with VEOLIA, carried out six weeks of experimental campaigns between November 2008 and July 2009 in the vicinity of an energy recycling unit. The atmospheric dispersion of the plume was studied by SF_6 tracer injection in the 40 m high stack. Maximal values of experimental Atmospheric Transfer Coefficient (ATCmax) and horizontal dispersion standard deviations (σ_h) were compared to the results of the first generation Gaussian models, Doury and Briggs, and to the results of the last generation Gaussian models, ADMS 4.1 (Atmospheric Dispersion Modelling System). Several modelling parameterization for ADMS 4.1 computations were tested and revealed an overestimation of the σ_h with the building option or with the integration of a surface roughness file. Consequently, ADMS 4.1 was used without model options. The Doury and Briggs models were combined with Holland formulation for the effective height calculation. In neutral atmospheric conditions and in summer unstable conditions (class A, B and C according to Pasquill classification), the ADMS 4.1 model is appropriate to estimate ATCmax

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value but overestimates in some cases. It was noticed that, during wintry periods and in class C atmospheric conditions, all of these models overestimated ATCmax for distances from the release point comprised between 0 and 2000 m. To estimate the atmospheric dispersion of an industrial release with a commercial model, as ADMS 4.1, without a prior comparison with an experimental data base dedicated to the studied site, can induce a poorly suitable modelling parameterization and leads to uncertainties difficult to quantify on the dispersion conditions.

Keywords: atmospheric dispersion, rural environment, SF_6 tracer release, Gaussian models.

1 Introduction

Predicting the dispersion of accidental releases into the atmosphere and estimating their consequences for the population is a major challenge. Because of their simplicity and rapidity of calculation, Gaussian models are ideally suitable tools for this problem. The Gaussian model is a simplified solution of the diffusion transport equation, which describes the spatial evolution of the concentration of a pollutant in the event of a constant release under uniform meteorological conditions. The use of a Gaussian model requires the standard deviation of the dispersion to be determined. For first generation Gaussian models, such as the models of Pasquill [1], Briggs [2] and Doury [3], the standard deviations for dispersion have been determined from experimental campaigns and are valid for the experimental conditions under which they were established, mainly from releases at ground level and over flat or slightly hilly terrain. A new generation of Gaussian models, such as the ADMS 4.1 model developed by CERC [4], has made it possible to determine the dispersion of industrial releases into the atmosphere as a function of the characteristics of the atmospheric boundary layer and the characteristics of the site: buildings, roughness, etc. The aim of this study is to evaluate the ability of the ADMS 4.1 model to reproduce dispersion phenomena for an elevated release with plume rise, by comparing the dispersion calculations with those deduced from an experimental data base and from calculations with first generation Gaussian models.

In order to acquire an understanding experimental data base of near-field atmospheric dispersion, IRSN in collaboration with VEOLIA, carried out six weeks of experimental campaigns in the vicinity of an energy recycling unit between November 2008 and July 2009. The dispersion of the atmospheric releases was studied with injections of SF_6, a passive tracer, via the 41 m-high stack. Ground samplings allow evaluating the maximal values of the Atmospheric Transfer Coefficient (ATCmax) and the horizontal dispersion standard deviation (σ_h) up to a distance of 4.2 km from the release. Measurements were carried out during a wide range of meteorological conditions, which allow us to evaluate the plume dispersion during neutral and unstable atmospheric conditions.

2 Experimental campaigns: equipment and methods

2.1 Experiment site

The atmospheric dispersion campaigns were held from 17 to 28 November 2008, from 19 to 29 January 2009 and from 29 June and 10 July 2009 in the vicinity of an Energy Recycling Unity (EUR) on a rural plain, characterized by wooded surfaces and vegetable and cereal growing. The main building of the EUR is a 36 m high building, and is equipped with a 41 m high stack, that is 5 m above the build roof. The discharge conditions are given in table 1. Temperature and flow rate features induce a plume rise.

Table 1: Discharge conditions of the EUR.

Release height	41 m
Stack diameter	1.3 m
Flow rate	60000 $Nm^3.h^{-1}$
Temperature	145°C
Release velocity	20 $m.s^{-1}$

2.2 SF_6 release methods, sampling and measurements

To study the atmospheric dispersion of the EUR release, a passive tracer, the SF_6, was injected through the stack. Releases were realized with duration of 30 minutes and a constant generation rate of 5.4 $g.s^{-1}$. The system used a SF_6 bottle (Messer, France), connected to a mass flowmeter (Sierra 820) and installed on a balance to control the released mass. For ground measurements, atmospheric sampling were carried out into Tedlar bags using thirty autonomous gas sampling devices, spaced every 2 to 3° along axis perpendicular to the mean wind direction. Gas sampling devices allow doing consecutively 2 or 5 sample collections of nine minutes each. Among these samplings, it was chosen for data processing, the sampling for which, there was the best agreement between the wind direction and the transit time of the SF_6 plume.

SF_6 analyses were conducted by Gas Chromatography with electron capture detector (CPG-ECD, AUTOTRAC 101 Tracer Gas Monitor, Lagus Applied Technology Inc). The detection limit is 25 ppt, with an accuracy of ± 3%.

2.3 Acquisition of meteorological data

Instrumental meteorological devices were set on the industrial site. Turbulent parameters and wind direction and velocity were evaluated at a 10 m height with an ultrasonic anemometer (Young 81000), operating at 20 Hz. The turbulent parameters (friction velocity, kinematic heat flux and Monin Obukhov length, roughness length) were derived via eddy-correlation. Roughness length and inverse length of Monin-Obukhov were correlated according to the works of Golder [5] to determine the atmospheric stability. Temperature, atmospheric pressure, global radiation and pluviometry were measured at a 1.5 m height with a meteorological station (AHLBORN).

Meteorological and turbulent data used for dispersion modelling are averaged on the duration of discharge and sampling.

3 Experimental results

3.1 Data processing

The measurements of SF_6 concentration are used to determine the maximal atmospheric transfer coefficients value (ATCmax) evaluated for each measurement axis, expressed according to eqn (1):

$$ATC_{\max} = \frac{\int_{t0}^{t1} X(M,t).dt}{\int_{t'0}^{t'1} q(t).dt} \tag{1}$$

- X(M,t): maximal SF_6 concentration (ppb), measured along a radial,
- q(t): SF_6 release rate, in $m^3.s^{-1}$,
- t'_0, t'_1: instant of the beginning and end of source emission in s,
- t_0, t_1: instant of the beginning and end of measurement in s.

The SF_6 tracer dispersion was also studied in terms of plume form, in order to check if the Gaussian dispersion is correctly represented by the experimental results. To achieve this, a Gaussian was fitted to our field data (for each radial performed).

3.2 The data base description

Among the forty four releases studied during the three campaigns, only measurement radials for which there was a good coherence between the sampling location and the wind direction were used for the comparison between the ATC_{max} which was observed (ATC_o) and the ATC_{max} which was predicted (ATC_p) (exploitation rate: 75%). According to the Pasquill classification, twenty radials were realized in neutral atmospheric condition (class D), and eighteen in unstable conditions: ten in class C, four in class B and four in class A. Measurements were carried out at distances from the release point ranging from 100 m to 4160 m. Some SF_6 releases were performed, during the UVE stops, with temperature less than 32°C. Values of experimental σ_h and ATC_o for various distances are indicated in table 2 for neutral atmospheric conditions and in table 3 for unstable atmospheric conditions.

In neutral conditions and for release performed at 145°C, the maximal impact of the plume, is located at a distance ranging from 1000 to 1500 m from the release point with an ATC_o in the order of 5.0 10^{-6} to 1.0 10^{-5} $s.m^{-3}$; for greater distance, the value of ATC_o gradually decreases to reach 10^{-7} $s.m^{-3}$ at 3250 m. It can be noticed an atypical value of 1.1 10^{-6} at 3640 m. In the case of cold releases and whatever the distance, the ATC_o value is one order of magnitude greater than in the case of warmer releases.

During winter days, in unstable conditions (Class C and B), the ATC_o is about 10^{-7} $s.m^{-3}$ at 400 m from the release and increases with the distance up to a factor of five. During summer days in stability class C, an opposite behaviour is observed; the plume impact is maximal at 245 m from the release with an ATC_o value of 7.6 10^{-6} $s.m^{-3}$ and decrease to reach a value of 1.1 10^{-6} $s.m^{-3}$ at 2090 m. In atmospheric stability class A, ATC_o is weaker of one order of magnitude than in class C.

The standard deviation of the horizontal dispersion varied between 36 and 280 m, it can be noticed that the evolution of σ_h in function of the release distance is similar in neutral and unstable condition.

Table 2: ATCo and σ_h deduced from experimental campaigns in neutral atmospheric conditions and related experimental conditions: distance from release, and wind speed at 10 m height. Grey lines correspond to SF6 release performed with cold temperature.

Date	Distance from release (m)	Discharge temperature (°C)	Stability Class	U ($m.s^{-1}$)	ATCo ($s.m^{-3}$)	σ_h (m)
08/07/09	100	145	D	3.8	0	–
07/07/09	104	145	D	7.3	4.1 10^{-6}	–
23/01/09	570	145	D	11.4	1.2 10^{-5}	36
22/01/09	730	145	D	9.9	3.7 10^{-6}	70
22/11/08	850	106	D	5.6	1.0 10^{-5}	60
22/01/09	1480	146	D	9.8	4.0 10^{-6}	86
22/11/08	1590	17	D	5.8	1.1 10^{-5}	100
23/01/09	1650	145	D	11.4	2.8 10^{-6}	–
08/07/09	1650	145	D	4.8	2.9 10^{-6}	82
22/01/09	1670	145	D	9.9	2.0 10^{-6}	132
08/07/09	1706	145	D	3.8	1.2 10^{-6}	83
24/01/09	1760	143	D	3.4	2.5 10^{-7}	80
19/11/08	1800	17	D	3.7	5.0 10^{-6}	165
24/11/08	2020	145	D	3.6	8.1 10^{-7}	110
20/11/08	2090	15	D	4.4	8.6 10^{-6}	80
07/07/09	2180	145	D	7.3	9.6 10^{-7}	152
07/07/09	2660	145	D	7.3	6.7 10^{-7}	280
27/01/09	3250	145	D	3.0	3.2 10^{-7}	165
21/11/08	3515	13	D	7.2	2.0 10^{-6}	250
23/01/09	3640	150	D	11.6	1.1 10^{-6}	250

Table 3: ATCo and σ_h deduced from experimental campaigns in unstable atmospheric conditions and related experimental conditions: distance from release, wind speed at 10 m height. Grey lines correspond to SF6 release performed with cold temperature.

Date	Distance from release (m)	Discharge temperature (°C)	Stability Class	U ($m.s^{-1}$)	ATCo ($s.m^{-3}$)	σ_h (m)
27/11/08	400	145	C	4.3	$1.1\ 10^{-7}$	–
27/01/09	730	143	C	3.9	$1.7\ 10^{-7}$	57
27/11/08	1010	145	C	4.3	$1.5\ 10^{-7}$	–
21/01/09	1215	146	C	3.7	$3.4\ 10^{-7}$	90
27/11/08	1940	145	C	4.3	$5\ 10^{-7}$	100
27/01/09	2995	143	C	3.9	$6.0\ 10^{-7}$	178
07/07/09	245	145	C	5.5	$7.6\ 10^{-6}$	–
06/07/09	629	145	C	5.6	$5.0\ 10^{-6}$	44
07/07/09	2073	145	C	5.5	$2.3\ 10^{-6}$	101
06/07/09	2090	145	C	5.1	$1.1\ 10^{-6}$	146
28/01/09	1260	143	B	3.2	$3.1\ 10^{-7}$	70
28/01/09	4160	143	B	3.2	$4.7\ 10^{-7}$	230
01/07/09	912	30	B	3.2	$1.7\ 10^{-6}$	96
01/07/09	1000	32	B	1.9	$7.5\ 10^{-6}$	105
03/07/09	700	145	A	3.23	$4.0\ 10^{-7}$	–
02/07/09	1395	145	A	2.3	$5.6\ 10^{-7}$	–
03/07/09	1714	145	A	3.23	$4.8\ 10^{-7}$	150
02/07/09	3080	145	A	2.3	$8.0\ 10^{-8}$	–

4 Comparison with Gaussian models

4.1 Description of ADMS 4.1, Briggs and Doury models

Three Gaussian plume atmospheric dispersion models were used to predict the ATC around the site, the ADMS 4.1 model [4], the Briggs model [2] and the Doury model [3].

The main difference between these models is that ADMS 4.1 uses a more modern method of boundary layer scaling, the Monin-Obukhov length, which allows for vertically inhomogeneous turbulence in the atmosphere to be modelled. ADMS 4.1 uses a Gaussian concentration distribution to calculate the dispersion of releases under stable and neutral conditions [6, 7] and a skewed distribution in the case of unstable conditions [8, 9]. Moreover, it contains several modules which enable to take into account the effects of buildings, topography and roughness on the dispersion and on the trajectory of the plume [10, 11].

Several modelling parameterization for ADMS 4.1 computations were tested and revealed a strong overestimation of the plume width with the building option or with the integration of a surface roughness file. Consequently, ADMS 4.1 was used without these model options. The meteorological and micro-meteorological data set allow testing the sensitivity of the model to the meteorological parameter inputs. For each atmospheric stability condition, the modelling configuration, that allows the best correlation between ATC_o and ATC_p, was retained for comparison with ATC_p calculations performed with Doury and Briggs models. In neutral conditions, the following meteorological parameters were considered: wind velocity and direction, temperature, humidity, global radiation and roughness length measured on site. In unstable conditions, the following meteorological parameters were considered: Monin Obhukhov length, kinematic heat flux, wind velocity and direction, temperature, humidity and a constant value of roughness length (z_0 = 0.02 m).

The Briggs' formulations of standard deviations for dispersion are function of the Pasquill stability classes and of the distance from the release point [2]. Pasquill stability classes consider 6 atmospheric stability ranges from very unstable (A), to very stable (F). On the other hand, the Doury standard deviations are function of the transfer time and of only two classes of atmospheric stability: normal diffusion and weak diffusion [3]. Normal diffusion is defined by a vertical temperature gradient less than or equal to -0.5°C/100 m and corresponds to unstable or neutral atmospheric conditions. Weak diffusion is defined by a vertical temperature gradient greater than -0.5°C/100 m and is equivalent to stable or very stable atmospheric conditions. The Doury and Briggs models were combined with Holland formulation [12, 13] for the calculation of the effective height (H_{eff}):

$$H_{eff} = z_s + \Delta h \tag{2}$$

- z_s : source height (m),
- Δh : plume rise (m) :

$$\Delta h = 2.2 \frac{V_s d}{\bar{u}} + 418 \frac{W}{\bar{u}} \tag{3}$$

- V_S : discharge velocity (m/s),
- d : stack diameter (m),
- $\bar{u}$: wind velocity at the discharge height (m/s),
- W : thermal flow (W)

The wind velocity at the discharge height was calculated according to the Businger-Dyer relationship [14].

4.2 Comparison with the experimental results

In order to compare our experimental results to the dispersion calculations with Briggs, Doury, ADMS 4.1 models, the ratios $\sigma_{h\_p}/\sigma_{h\_o}$ and ATC_p/ATC_o are shown for neutral conditions in figures 1 and 2 and, for unstable conditions, in figures 3 and 4. The statistical parameters (mean, median, standard deviation) of those ratios are given in tables 4 and 5.

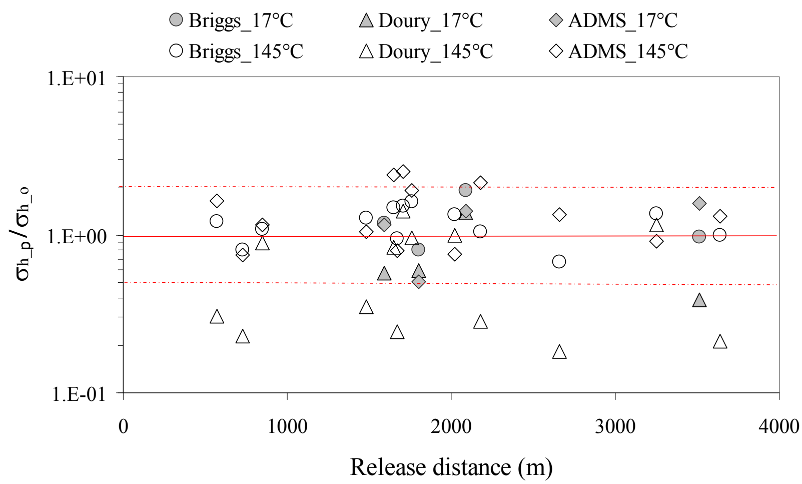

Figure 1: Comparison of the ratios $\sigma_{h\_p}/\sigma_{h\_o}$ for Briggs, Doury and ADMS 4.1 models as a function of the release distance and of the temperature discharge in neutral atmospheric conditions (class D according to Pasquill classification).

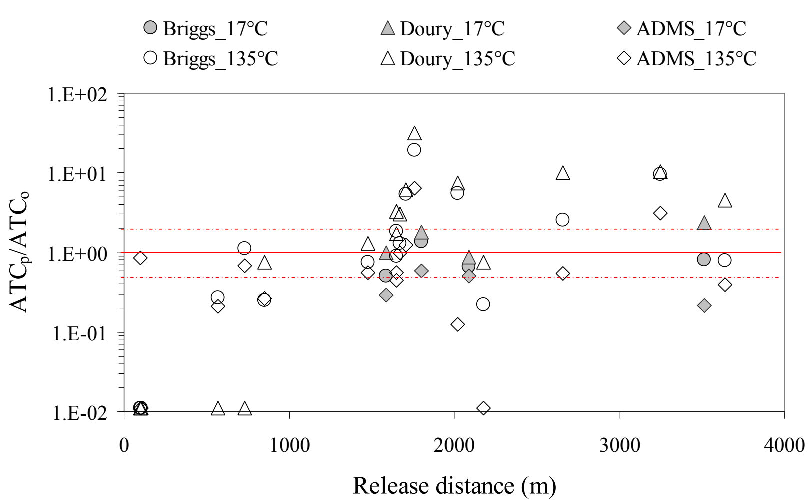

Figure 2: Comparison of the ratios ATC_p/ATC_o for Briggs, Doury and ADMS 4.1 models as a function of the release distance and of the temperature discharge in neutral atmospheric conditions (class D according to Pasquill classification).

In neutral conditions, the most appropriate model to provide the σ_h is the Briggs model ($\sigma_{h\_p}/\sigma_{h\_o}$ mean = 1.19). The Doury model underestimates the calculation of σ_h of 35% in mean, while the ADMS 4.1 model tends to overestimate σ_h of 37% in mean.

In terms of ATC, ADMS 4.1 achieves a good agreement with the measurements (ATC_p/ATC_o mean = 1.19). For warm releases, the Doury and the Briggs models overestimate the ATC value up to a factor 5. For cold releases, the ATC results for the Doury and the Briggs models are much better; the mean ratio ATC_p/ATC_o is respectively of 1.51 and of 0.84. Thus, the Holland formulation for plume rise does not seem to be appropriate for this discharge configuration.

Table 4: Comparison of the mean, the median and the standard deviation calculated for the ratios $\sigma_{h\_p}/\sigma_{h\_o}$ and ATC_p/ATC_o for Briggs, Doury and ADMS 4.1 models in neutral atmospheric condition (class D according to Pasquill classification).

		ADMS 4.1	Briggs	Doury
$\sigma_{h\_p}/\sigma_{h\_o}$	**mean**	1.37	1.19	0.65
	median	1.37	1.18	0.57
	standard deviation	0.59	0.33	0.42
ATC_p/ATC_o	**mean**	1.02	3.11	5.08
release at T = 145°C	**median**	0.54	1.00	2.35
	standard deviation	1.61	5.05	7.99
ATC_p/ATC_o	**mean**	0.40	0.84	1.51
release at T < 32°C	**median**	0.40	0.73	1.40
	standard deviation	0.17	0.38	0.70

Table 5: Comparison of the mean, the median and the standard deviation calculated for the ratios $\sigma_{h\_p}/\sigma_{h\_o}$ and ATC_p/ATC_o for Briggs, Doury and ADMS 4.1 models in unstable atmospheric condition (class D according to Pasquill classification).

		ADMS 4.1	Briggs	Doury
$\sigma_{h\_p}/\sigma_{h\_o}$	**mean**	1.80	1.81	0.83
	median	1.66	1.57	0.80
	standard deviation	0.78	0.47	0.36
ATC_p/ATC_o	**mean**	6.17	18.31	21.81
Winter days	**median**	3.40	11.71	16.80
	standard deviation	6.51	19.27	18.68
ATC_p/ATC_o	**mean**	1.53	2.44	11.94
Summer days	**median**	0.84	1.49	8.25
	standard deviation	2.22	2.85	12.58

In unstable conditions, the most appropriate model to provide the σ_h is the Doury model ($\sigma_{h\_p}/\sigma_{h\_o}$ mean = 0.83), whereas the Briggs and the ADMS 4.1 models, which deliver similar results ($\sigma_{h\_p}/\sigma_{h\_o}$ mean = 1.8), overestimate this parameter (fig.3).

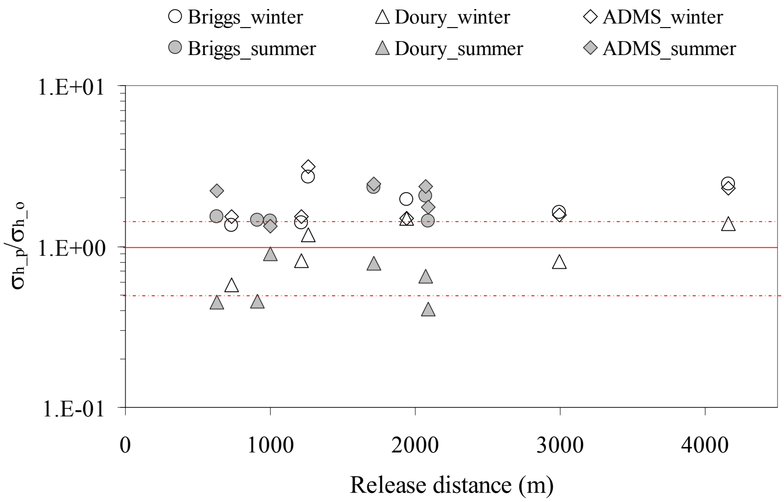

Figure 3: Comparison of the ratios $\sigma_{h\_p}/\ \sigma_{h\_o}$ for Briggs, Doury and ADMS 4.1 models as a function of the release distance and of the temperature discharge in unstable atmospheric conditions (classes A, B, C according to Pasquill classification).

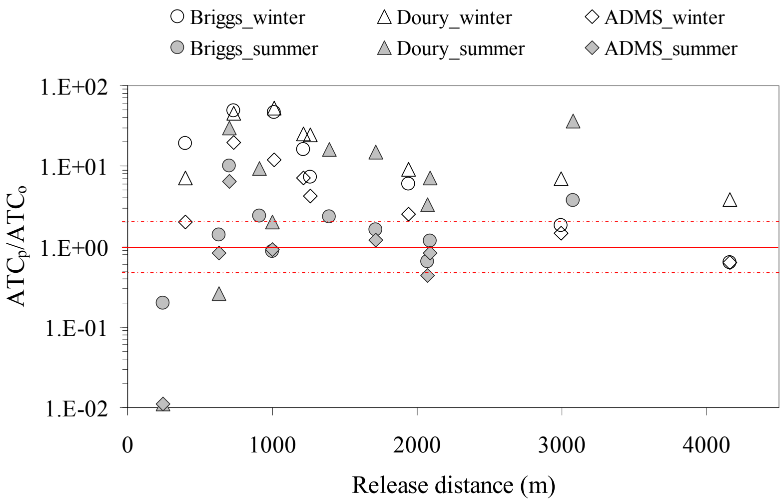

Figure 4: Comparison of the ratios ATC_p/ATC_o for Briggs, Doury and ADMS 4.1 models as a function of the release distance and of the temperature discharge in unstable atmospheric conditions (classes A, B, C according to Pasquill classification).

In unstable conditions on winter days, none of the models accurately evaluate the ATC_o at distances less than 2000 m from the release point; ADMS 4.1 overestimates the ATC_o value of a factor 2 to 20 and the models of Briggs and Doury of a factor 6 to 50. For radials performed at 2995 and 4160 m, the ATCp/ATCo ratio calculated with Briggs and ADMS 4.1 models is lower than two, whereas the one calculated with Doury model varied between three and five.

In unstable conditions on summer days, the ADMS 4.1 models is the most adapted to evaluate the ATC_o; the mean of the ATC_p/ATC_o ratio is about 1.53 and the median about 0.84. The Briggs model over-estimates, in mean, the ATC_o with a factor 2.5 and the Doury model with a factor 12. The Holland formulation for the effective height calculation of the plume, combined with Briggs model, in this discharge configuration, allows a better agreement between the ATC_o and the ATC_p in unstable condition during summer days than in winter days. This formulation does not suit to the dispersion calculations with the Doury model.

5 Conclusion

This study allowed us to obtain ATC values in rural environments in the case of an elevated release for different atmospheric stability conditions.

In neutral condition and in unstable conditions during summer days, whatever the distance from the release point, the most appropriate model to simulate the SF_6 plume dispersion is ADMS 4.1. It can be noticed however that ADMS 4.1 tends to overestimate the plume width. To reach this result a parametrical study was necessary; used with the building option or with the integration of a surface roughness file, the ADMS 4.1 model highly overestimates the σ_h. Consequently, ADMS 4.1 was used without model options.

During winter days, in unstable conditions (Class C and B), for distance less than 2000 m, the ATC_o value is inferior of one order of magnitude than during summer days. The three models overestimate the ATC_o in this condition up to a factor 50.

Although, the Holland formulation for the plume rise calculation, combined with Briggs model, allows a better agreement between the ATC_o and the ATC_p than combined with the Doury model, this formulation does not seem to be appropriate for this discharge configuration. Other plume rise formulations should be tested.

To estimate the atmospheric dispersion of an industrial release with a commercial model, as ADMS 4.1, without a prior comparison with an experimental data base dedicated to the studied site, can induce a poorly suitable modelling parameterization and leads to uncertainties difficult to quantify on the dispersion conditions.

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