H13-77

SMOKE DISPERSION FROM LOW STACKS ON PITCHED-ROOF BUILDINGS: MODEL CALCULATIONS USING WINMISKAM IN COMPARISON WITH WIND TUNNEL RESULTS

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Abstract: Studies in many European countries have revealed that residential wood combustion is a very significant source of particle pollution. In Denmark this source contributes to more than half of the national $PM_{2.5}$ particle emissions. Both air pollution from residential wood combustion and traffic are local scale problems, which for certain questions demand a detailed description of the flow around buildings.

In the present work a prognostic flow model was applied in order to improve the understanding of the dispersion conditions governing the highest pollutant loads, and to produce recommendations regarding the optimal position and height of the stack depending on the type of roof. Specifically, this paper presents CFD simulations with MISKAM of pollutant dispersion from a domestic stack over an isolated building with flat or pitched roof. A number of basic cases have been studied that demonstrate the influence of the relative stack height and the slope of the roof on plume dispersion. To our knowledge, it is the first time that MISKAM is being engaged on the simulation of that type of configurations. The results are compared against a wind tunnel study, conducted to investigate the dispersion of smoke released from domestic stacks.

Previous studies have documented that MISKAM can be considered as one of the well established CFD tools for atmospheric dispersion studies in built-up areas. However, this study also has revealed a need for further studies of some of the assumptions and algorithms in MISKAM. The above statement is demonstrated with specific examples.

***Key words:** atmospheric pollution; modeling; MISKAM; CFD; smoke; stack; chimney.*

INTRODUCTION

Due to increasing oil prices the use of domestic wood combustion has increased significantly in the recent years. Studies in many European countries have revealed that residential wood combustion is a very significant source of particle pollution (Bari *et al.*, 2009). In Denmark this source is responsible for more than half of the direct $PM_{2.5}$ particle emission in the country (Glasius *et al.*, 2008). Both air pollution from residential wood combustion and traffic are a local scale problem that demand detailed description of the flow around building obstacles. This being the case, attention was drawn to the development of atmospheric dispersion models and to the actual study of the phenomena through wind tunnel experiments.

The simulation of the atmospheric dispersion, is usually conducted with two types of models (Hunt *et al.*, 2003): the Fast Approximate Models (FAM) and the Fully Computational Models (FCM). In detail, FAM are mainly empirical models (Britter and Hanna, 2003) based on extensive field and wind tunnel studies. As a result, their application is recommended for, or sometimes limited to, the type of the topology for which they were designed. On the other hand, FCM are based on the numerical solution of the momentum, energy and mass transport equations. They can be applied on almost all types of topologies, but their applicability is limited by the required computational power and time. In general, the choice of the model depends on its practical purpose (in relation to dispersion modeling), the required level of spatial/temporal detail and scientific understanding involved, and on the detail and accuracy of meteorological and topographical input data. In this work, MISKAM (version 5.0) was selected as it is one of the well established CFD software tools in the field of atmospheric dispersion in built-up terrain. Considering pollution from traffic sources, Ketzel *et al.* (2000) compared it with OSPM (Berkowicz, 2000), a semi-empirical model, and with field measurements, and the results were in good agreement. Dixon *et al.* (2006) applied it also with success in similar configurations. Recently, MISKAM has been successfully applied on simple stack-building configurations (Olesen *et al.*, 2009) and a large urban setting (Eichhorn and Balczo, 2008). However, more wind tunnel and field experiments are necessary for the validation of MISKAM and all other atmospheric dispersion models.

Several wind tunnel studies have been undertaken in order to investigate dispersion from sources close and over building/s of various dimensions. Huber (1989) examined, in a wind tunnel, the influence of the building width and orientation on the wind through concentration profiles in the near wake of the building. Kim *et al.* (1990), Higson *et al.* (1994) and Mirzai *et al.* (1994) have investigated flow and dispersion around individual or small groups of obstacles. Davidson *et al.* (1995; 1996) investigated the flow and dispersion through large groups of obstacles, both in field and wind tunnel experiments. MacDonald *et al.* (1997; 1998) have described the effect of obstacle aspect ratio on dispersion in obstacle arrays in field and wind tunnel experiments. Dispersion of atmospheric pollutants in the vicinity of isolated obstacles of different shape and orientation with respect to the mean wind has been examined in scaled field direction (2001; 2003; Mavroidis *et al.*, 1999) and wind tunnel experiments (Yassin *et al.*, 2008). White and Stein (1990) and Thompson (1991, 1993) conducted wind tunnel experiments to study the influence of the relative stack height on the downwind concentration.

This paper presents the CFD simulations with MISKAM of pollutant dispersion from a domestic stack over an isolated building with flat or pitched roof. Five basic cases have been studied that demonstrate the influence of the relative stack height and the slope of the roof to the plume's dispersion. To our knowledge, it is the first time that MISKAM is being engaged on the simulation of that type of configurations. Moreover, its results are compared against an unpublished wind tunnel study (Jensen, 1984), which was dealing with the diffusion of smoke released from domestic stacks.

METHODOLOGY

The details of the methodology followed for the validation of the CFD software MISKAM against the available wind tunnel experiments are described in this section. First, the theoretical characteristics of the CFD software MISKAM are described. Next follows an explanation of the studied geometry and meteorology, which both are major input parameters of the simulations. Finally, the studied cases are defined.

Numerical Simulation

For the numerical simulations the CFD software MISKAM (version 5.0) has been used. It is a microscale flow and dispersion model which was developed at the University of Mainz, Germany, for urban pollutant dispersion simulations (Eichhorn, 2002). Engineering Bureau Lohmeyer, in Karlsruhe, developed the user interface WinMISKAM. Each released version of MISKAM is evaluated according to the VDI guideline 3783 Part 9 (VDI, 2005).

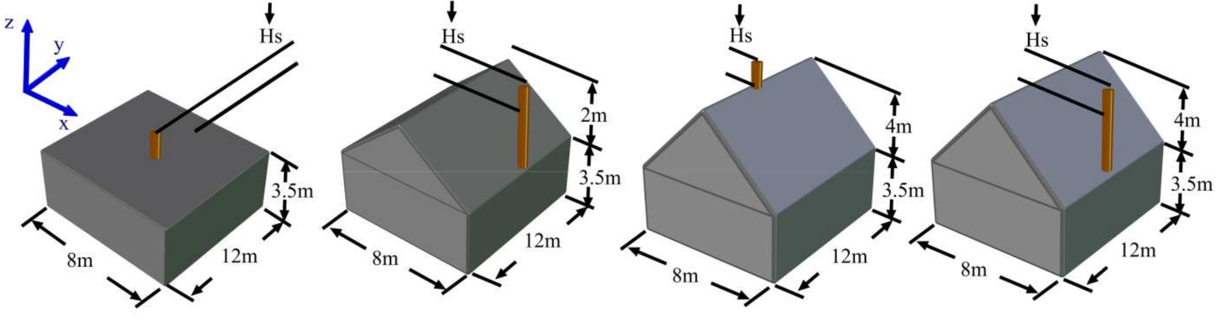
MISKAM solves, by the finite difference method, the Reynolds averaged Navier-Stokes equation with a modified k-ε turbulence closure on a non-uniform Cartesian grid for the flow field. The dispersion of the gas is approximated as transport of a passive scalar by the Eulerian advection-diffusion equation. Some of the drawbacks of MISKAM are: i) The modeled area can not contain steep relief; ii) Buildings are modeled with blocks (parallel to x and y axis), while slanted roofs can only be represented by a step like structures; iii) Chemical reactions cannot be modeled; iv) Sources are represented by volume sources; v) Only neutral thermal stratification is allowed. The advection equations are solved using the first order upwind numerical scheme but as an option, first or second order Smolarkiewicz correction factor can be applied. In short MISKAM (and WinMISKAM) are commercial products and can be considered “black boxes” from the user's perspective. For instance, only one numerical solver is available.

Nevertheless, owing to the predefined application field (microscale dispersion) and its simplified user interface, no advanced knowledge on fluid mechanics is required. Therefore, the model is widely employed for regulatory purposes at various environmental agencies, consulting organizations and experts throughout Europe. MISKAM has been extensively used and validated in many research projects (Dixon *et al.*, 2006; Eichhorn and Balczo, 2008; Ketzel *et al.*, 2000; Olesen *et al.*, 2009). As a result, it is considered one of the well established CFD software for microscale atmospheric pollution studies.

Studied Geometry

The studied geometry originates from a series of wind tunnel experiments performed in 1983 (Jensen, 1984). The aim of those experiments was a sensitivity analysis of the atmospheric dispersion of smoke released from residential stacks (chimneys). The physical model was constructed in the scale 1:100 and tracer gas concentrations were measured using different release conditions. Specifically the examined parameters were: i) The relative stack height (height from the top of the roof); ii) The slope of the roof; iii) The position of the stack; iv) The wind direction.

From all the building configurations, included in that study (Jensen, 1984), four were selected as more representative. The configurations and the dimensions of the buildings are illustrated in Figure 4. The first parameter, stack height, was studied in all building configurations. In order to study the next two parameters, slope of the roof and position of the stack, the chosen building configurations should be studied in pairs. The recommended pairs are: Figure 4a and c, and Figure 4b and d for the slope of the roof and Figure 4c and d for the position of the stack.



a) flat roof b) 30° roof stack @ middle c) 45° roof stack @ middle d) 45° roof stack @ downwind side

Figure 4. Schematic of the four building configurations that were selected from the wind tunnel experiments (Jensen, 1984). All dimensions refer to full-scale conditions.

Our study covered all the four configurations but only a few selected results for the configuration shown in Figure 4b will be presented in this paper.

Meteorology

The meteorological conditions play a significant role on the atmospheric dispersion of air pollutants. In the aforementioned wind tunnel study (Jensen, 1984), the inlet wind velocity profile for the relevant cases was characterized by $u^{*} = 0.28$ ms^{-1} and $z_o = 0.12$ m, and referred to neutral thermal stratification. Two different ratios of the gas exhaust velocity to wind velocity were considered (0.5 and 0.17, respectively).

Apart from the wind velocity, the influence of the wind direction was also examined in the wind tunnel study. Specifically, for all four geometries (Figure 4) the same wind direction was considered, but for the third geometry (Figure 4c) a variable wind direction was additionally employed

Case studies

Five basic cases derived with respect to the presented geometry (see Figure 4) and meteorology (varied wind direction on geometry Figure 4c). For some of these basic cases, extra situations were investigated. Their characteristics are described in more detail in the pertinent paragraphs of the following section. The CFD software, MISKAM employs the Finite Difference Method (FDM) to solve the differential momentum and mass transport equations. The FDM calculation mesh is a structured Cartesian grid and can be automatically generated in WinMiskam. Unfortunately, the available mesh generation procedure is lacking flexibility, especially for non-uniform mesh resolution. For this reason, a custom routine was developed in Microsoft Excel VBA. This routine: i) Divides the whole domain in custom regions parallel to x or y axis; ii) Takes as input the size of the domain and the building/s, and the expansion ratio for each region; iii) Calculates the x- and y- size steps for each region and defines the buildings and their roofs.

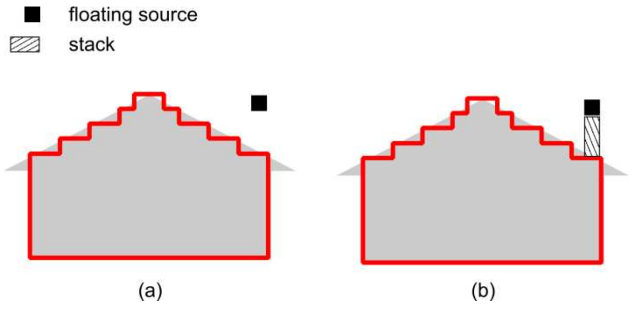


Figure 2. Schematic drawing of the real building (gray area) and the building used by MISKAM (bold line) a) floating source and b) physical stack.

In present work, the instructions of VDI 3783 part 9 (VDI, 2005) were followed to determine the appropriate resolution for each region. A crucial limitation, when using a Cartesian grid, is the fact that all the sides of the buildings have to be parallel to the axis. The same statement is also valid for the roofs of the buildings, but most of the related cases have pitched-roofs. As a result, the slope of the roofs has to be approximated by a stepwise structure. In Figure this is illustrated schematically. Furthermore, the smoke was considered to be emitted mainly by a floating source. In other words, the stack itself was not physically represented as an object (Figure).

This case is referred here to as the base case.

RESULTS

The setup of the MISKAM simulations is based on the methodology that was deployed in the previous section (Figure 4). After a first series of model simulations the results were examined, and subsequently supplementary simulations for a number of sub-cases were conducted. These supplementary simulations aimed to examine the sensitivity of MISKAM to various parameters and to identify the causes of poor agreement during some of the tests.

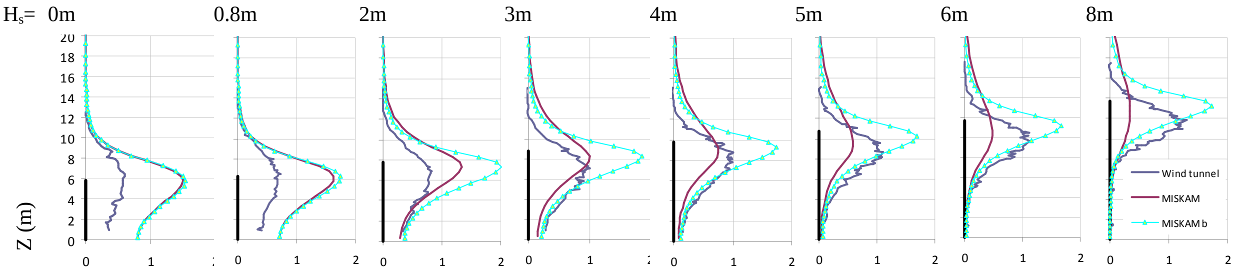


Figure 3. Case of the 30° roof building with the stack at the side. Normalized concentration ($C_{norm} = C/C_{max\ @\ Hs=3.0m}$) for various relative stack heights (Hs=0to 8m) at 15m downwind from stack. See further explanation of the normalization in the text. Results from Wind tunnel modeled (MISKAM) and modeled with physical representation of the stack (MISKAM b). The release height is also illustrated by solid vertical line. The stack height (H_s) refers to the height of the stack above the roof top...

Basic cases

MISKAM was able to estimate the input wind profile well. Though it was not possible to directly validate the profile at other points of the domain due to lack of wind tunnel results, the simulated wind field was considered satisfactory with qualitative criteria and in combination with the previous successful evaluation reports on MISKAM. The concentration data from the wind tunnel measurements were only available in form of strip chart drawings. Due to this, estimation of absolute concentration values was not possible. In order to make at least a qualitative comparison of model results with the measurements, a normalization procedure was applied to the data. All the measured and modeled concentrations were divided by the maximum concentration (measured/modeled respectively) for the case with H_s=3m. Using this procedure, one can examine the relative behavior of the measured/modeled concentrations, but comparison of the absolute values is not possible. The results for the Case of the 30° roof building with the stack at the side and for various relative stack heights (Hs=0 to 8m) are illustrated in Figure . Both the measured and the modeled profiles are given for a location corresponding to 15m downwind from the stack. Visual examination of the profiles reveals that for the shorter stacks (<3m) the wind tunnel data exhibit more rapid downward diffusion than the modeled concentrations. On the other hand, for taller stacks it is observed that the modeled plume is dispersed much more than indicated by the measurements. The elevated plume maximum concentration remains almost constant irrespective of height, while the model results show a rapid decrease of the plume maximum with increasing height. Because of this discrepancy, a number of model variations were applied and the results were compared with the base case.

Influence of momentum source

Usually, the plume exits the stack at a higher temperature than the ambient temperature and with some initial exit velocity. Both effects result in plume rise, which is usually denoted as buoyant and momentum rise, respectively. The basic cases with MISKAM considered no exhaust velocity. To test the influence of the exhaust velocity a momentum source was introduced at the highest point of the stack. The exhaust velocity was taken equal to 0.51 m/s, a value that originates from the defined exhaust velocity to wind velocity ratio (equal to 0.17 m/s). For the studied sub-cases the influence of the introduced momentum source was minimal, as a result, the momentum source was not applied further.

Influence of the dispersion correction approach

In convection-dominated problems, Finite Difference Method (as well as most other finite numerical techniques) introduces a numerical diffusion. MISKAM provides two options to deal with the induced numerical diffusion: i) first- and ii) second order Smolarkiewicz correction (Smolarkiewicz and Grabowski, 1990). All of them were tested, but no significant improvement was observed.

Physical representation of the stack

It was described earlier that initially the smoke was considered to be emitted by a floating source (Figure a) in order to simplify the geometry and the evaluation procedure respectively. Since this was a rather unjustified assumption, the floating source was replaced by a physically represented stack (Figure b). Unexpectedly, this change resulted in significant modification of the modeled concentration profiles (Figure – “Miskam b”). The agreement with the wind tunnel measurements seems even to be better, especially considering taller stacks. For the two shortest stacks (H_s=0 and 0.8m) the effect was however marginal. In order to elaborate in more details the apparent effect of a physical stack on model results, an examination of the turbulence data was conducted.

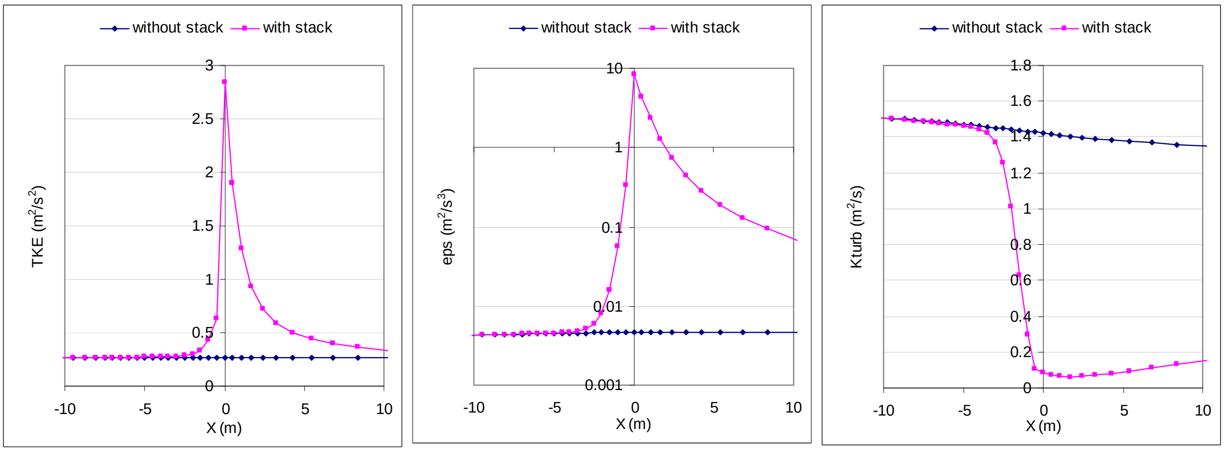


Figure 4. Longitudinal profiles of the modeled Turbulent Kinetic Energy (TKE), dissipation rate (eps) and the Turbulent Diffusivity (Kturb) for the cases without and with a physical stack. The profiles are taken at the source height for H_s=8m. x=0 at the stack.

Figure 4 shows profiles of the modeled Turbulent Kinetic Energy (TKE), dissipation rate (eps) and the Turbulent Diffusivity (Kturb) for the cases without and with a physical stack. The profiles are taken at the source height for H_s=8m and along the plume centerline. As one can see, the turbulent diffusivity coefficient exhibits a rapid decrease along the x axis due to presence of a physical stack in the model. This decrease is caused by a dramatic increase in the dissipation rate and the applied k-ε turbulence closure. Reduction of the turbulent diffusivity results in a more compact plume and apparently a better agreement with measurements. However, it is difficult to provide any physically reasonable explanation of the influence of a stack on the shown behavior of the turbulence parameters. Most likely, this effect is caused by some model deficiency in handling sharp isolated obstacles (in this case a stack) or even some numerical artifacts. Corresponding results (not shown here) for smaller stacks (<0.8m), reveal practically no influence of a physical stack on the turbulence.

CONCLUSIONS

In the present work, a CFD software (MISKAM) was employed for the simulation of smoke dispersion from domestic stacks. The results of the simulations were examined and compared with an experimental wind tunnel study for various single-building configurations. The investigated configurations included three different slopes of the roof (0°, 30° and 45°) and two positions of the stack (at the centre and at the downwind side). The sensitivity of the results on a number of parameters was examined in order to identify the causes of the observed variations.

One of the parameters was the inclusion of a momentum source - in order to simulate the exhaust velocity of the smoke - which results in insignificant variations. Similarly, the available dispersion correction factors, (Smolarkiewicz correction factor), did not show any significant influence on the model results. On the other hand, the replacement of the initial floating source with a physical stack represented in the model demonstrates an unexpected large influence on the results. It is, however, not possible to find any reasonable physical explanation of this effect. Therefore, a series of additional tests, plus a comparison with another CFD software (e.g. FLUENT) is required in order to explain the observed behavior. As a preliminary conclusion one can mention the following potential causes: i) the MISKAM approach to calculate the diffusion coefficient, ii) the mesh density recommended by the VDI 3783 guideline, iii) the inability of MISKAM to approximate realistically the sloped roofs, iv) the incorrect employment of the roughness of the vertical walls by MISKAM, v) the lack of sufficient data to examine MISKAM performance on the simulation of wind field (velocity, turbulent kinetic energy and dissipation).

ACKNOWLEDGEMENTS

A major part of the present work was conducted on a Short Term Scientific Mission funded by the COST Office under the COST action ES0602 "Towards a European Network on Chemical Weather Forecasting and Information Systems (ENCWF)". We are indebted to Prof. Jaakko Kukkonen for approving this STSM and to Prof. Ole Hertel for organizing and hosting it. The authors would also like to thank Dr. Allan Bang Jensen for making his wind tunnel data available for this study.

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