3.3

STACKS:
a new approach in atmospheric dispersion modelling

E.P. Weijers

KEMA

The Netherlands

STACKS: A NEW APPROACH IN ATMOSPHERIC DISPERSION MODELLING

E.P. Weijers[1]

ABSTRACT

Recently, KEMA Environmental Services completed several years of development of the STACKS model for atmospheric dispersion of air modelling. Not only the impact of conventional pollutants like SO_2 and NO_x are visualised. Exposure to nuclear particles and annoyance by odours can be effectively evaluated as well. Initially STACKS was developed for application by the electricity generating industry. Being an improvement over previous models, the Dutch government recognised the model as the foremost reference model for air quality modelling. STACKS uses modern insights in the use of meteorological data. Dispersion parameters are a continuous function of turbulence parameters instead of being determined by a discrete classification. In a separate module nuclear decay is estimated as function of plume arrival time. Validation experiments have been carried out to demonstrate its viability and the accuracy of its predictions.

INTRODUCTION

The use of atmospheric dispersion models

In the determination of the concentration levels around a source, experimental campaigns can be of use. However, these are often expensive and necessarily limited in time and space. Many companies need modelling of atmospheric dispersion of air pollutants when applying for environmental licences when existing facilities are enlarged or when process modifications are being considered. Obviously, the need for adequate mathematical tools, enabling a reliable simulation of the dispersion of air pollution, is evident here. Another reason in demanding such an adequacy is that (regional) authorities need the help of modelling techniques to assess an effective strategy in their control of air-pollution problems on the larger (regional) scale not only at the present but also in the future.

The use of sufficient dispersion modelling in order to quantify possible radioactive exposure is evident. Inadvertent radioactive emissions lead to the questioning of the safety in the local area. For this reason, the situation around nuclear power stations is constantly being monitored in the Netherlands. When industrial factories deal with radioactive material extended studies have to be carried out to estimate the local risks. Results of dispersion studies are used to set up an Emergency Preparedness Program.

In the Netherlands possibly adverse environmental effects due to (a change in) industrial activity have to be written down in so-called Environmental Impact Reports. In such a report one summarises, for example, ground level concentrations in the vicinity of an industrial site with are compared with governmental air quality standards. Those standards may be defined as the maximum admissible (hourly of daily) mean concentration in a year or refer to the higher percentiles.

Because critical environmental loads for several components are now being approached or even exceeded, requirements to individual industries are expected to become stricter. Differences between air concentrations and air pollution standards are small or negative. This is not expected to change drastically in the near future. Hence, quantitative determinations of individual contributions of stacks emission will remain necessary.

---

[1] KEMA, P.O. Box 9035, 6800 ET Arnhem, The Netherlands

FEATURES OF DISPERSION MODELLING

In modelling the pathway of pollutants through the air two items are important to consider [1]. First, a realistic description of the meteorological processes in the atmospheric boundary layer is necessary. Clearly, concentrations in air, location of (maximum) depositions and rate of changes of these variables are clearly affected by the prevailing atmospheric state (such as windspeed, winddirection, shear, temperature etc.). Second, dealing with individual plumes originating from separate emission sources, knowledge of the properties of plume and stacks is essential.

Viewed from the perspective of dispersion modelling, essential (boundary layer) meteorological parameters to be built in are:

- mean wind field (more specifically, its vertical gradients) and turbulent deviations
- scaling parameters (like friction velocity and Monin-Obukhov length) describing the state of the atmospheric in a 'universal' way
- height of the atmospheric boundary layer

When simulating the plume's behavior further information is necessary on:

- emission data (emission rate, flow rate, temperature)
- stacks characteristics (height, diameter)
- plume rise
- assumptions on gaussian or non-gaussian shape of the plume
- chemical reactions in production or removal processes

As an illustrative example of how some of these variables might affect concentrations on the ground consider the following two extreme conditions. In summer during the daytime, strong insolation may result in a quick dilution of the smoke plume (left picture in figure 1). Due to the relatively high temperatures, the formation of oxidant (O_3 and NO_2) takes places abundantly. In winter, insolation at high latitudes is weak resulting in less turbulence, a shallow boundary layer, less dispersion of the plume, and slower conversion rates. On average, the height of the atmospheric boundary layer in winter lies between 100 and 300 m. Plumes from tall stacks are now frequently transported beyond the top of this layer, as illustrated in the right picture of figure 1. Modern estimations have revealed that with a stacks height of 100 m only 25% will be dispersed within the boundary layer and contribute to the concentrations at ground level.

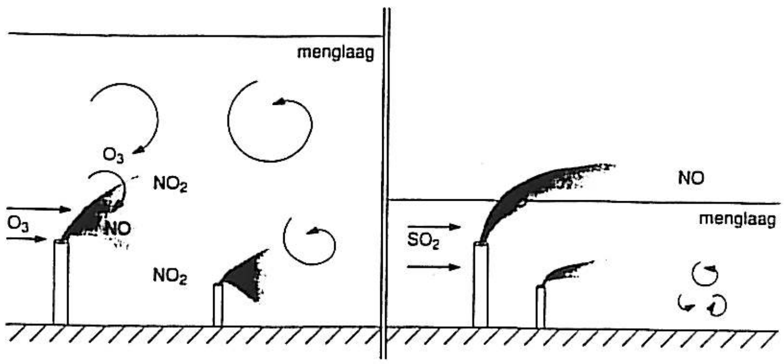

Figure 1

FEATURES OF TRADITIONAL AND ADVANCED MODELS

Traditional models make use of concepts that were developed in the sixties and seventies. At that time, classification of meteorological parameters in general was necessary because computations were carried out by hand or available computers did not have enough capacity. They focussed on methods that denote the degree of existing turbulence in the atmoshere in a fairly rough manner; the most popular example is the Pasquill stability classification. Here, atmospheric turbulence has been divided into six classes. To each class a fixed value for the atmospheric boundary layer height has been attributed. In later studies and experiments it appeared that such values were mostly chosen too high. Furthermore, the estimation of plume rise was known to be insufficient. One of the consequences of these failures were that contributions of high industrial stacks were seriously overestimated, as can be understood from the example above.

In the eighties a more physical approach led to models that did not use any classification at all but coupled simple scheme directly to physically meaningful parameters. All these models use the gaussian concept as a starting point with the determination of the height of the plume axes and the determining dispersion parameters σ_y and σ_z (see figure 2).

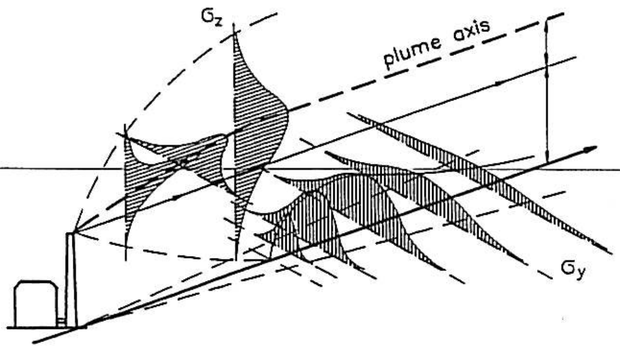

Figure 2 The gaussian plume concept

In its simplest formulation, dispersion parameters are coupled to characteristic meteorological parameters like σ_v, σ_w (turbulent components of wind speed in the lateral and vertical direction) and T_L (characteristic value for the time scale of the prevailing turbulent processes). This approach was stimulated because of the successful performance in describing air-borne concentrations [2]. The main advantage of this approach is the continuous treatment of turbulence instead of the discreet Pasquill classification. Dispersion coefficients are now calculated directly by using physically-based formulations which take into account the rate atmospheric turbulence and the explicit behavior of the height of inversion. Advanced modelling further benefits from improved insights in the mechanisms of surface reflection, (partial) inversion penetration and the layered structure of the atmosphere.

The KEMA model STACKS is an example of advanced modelling system in the determination of concentrations of pollutants in the air [3]. STACKS is an acronym for: Short Term Air Pollutant Concentration: KEMA Modelling System. The success of the implementation of modern boundary layer physics became apparent after experimental validations. In the early stages, meteorological formulations used in the dispersion model STACKS described the behaviour of turbulence in most of atmospheric boundary layer. In order to apply the model in roughly the lowest 50 m of the atmosphere the use of specific formulations was necessary describing the deviating turbulence in the so-called atmospheric surface layer. The reason for this is obvious: many polluting sources are located just above the earth's surface.

VALIDATION

Validation of STACKS is restricted here for application in the surface layer[4]. The comparison with measured concentrations occurred with dispersion data from an experiment with a low continuous source [5]. In this experiment (Prairie Grass) sulphur dioxide was released at a height of 0.46 m. Monitoring took place on a plain of short grass. Concentrations were measured at source distances of 50, 200 m and 800 m. The height of the measurements was 1.5 m. Crosswind integrated concentrations were calculated for sixty runs, which were carried out during all kind of atmospheric conditions. Figure 3 shows the relationship between modelled and measured (crosswind integrated) concentrations.

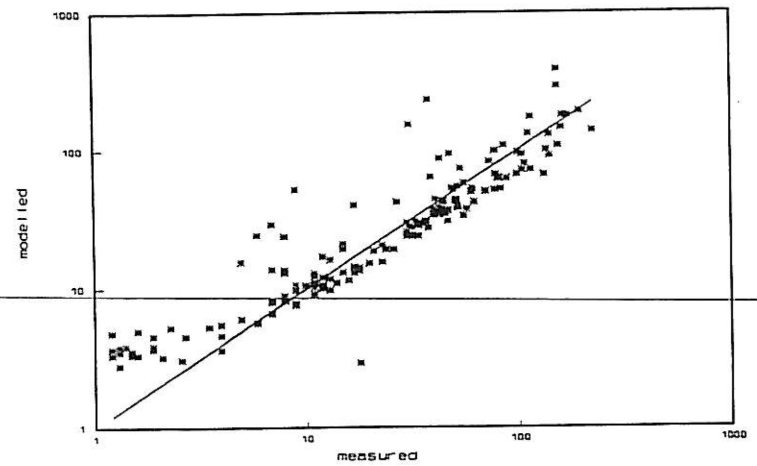

Figure 3. Modelled vs. Prairie Grass concentrations (x10^3) as found for a plume within the surface layer. The integrated concentrations are divided by the strength of the source.

Linear regression analysis calculates a slope of 0.96 and a correlation coefficient of about 0.80. 88% of all measurements is within a factor of two of the model values.

THE STACKS MODEL IN DAILY PRACTICE

Recently KEMA Environmental Services completed several years of development of the STACKS model for atmospheric dispersion of air pollutants [6]. Not only the impact of conventional pollutans like SO_2 and NO_x are visualised by STACKS. Particulate matter (PM25 and smaller) and annoyance by odours can be effectively evaluated as well. Initially STACKS was developed for application by the electricity generating industry, and therefore restricted to higher stacks. At a later stage its application was extended and validated for lower and surface sources. STACKS proved to be such an improvement over traditional modelling that the Dutch government now recognises the model as the foremost reference model for air quality modelling. In practice, this means that model implementations are now tested for effectiveness and accuracy by comparing them to the exacting standards of STACKS.

STACKS calculates the impact of one or more emitting sources (point or area) at user defined receptor points for distances up to a distance of 25 km. The calculation of concentrations and depositions apply to all important pollutants. Both short (3 min, 1, 8 or 24 h) and long term averages (monthly or yearly) at ground level can be given. Percentiles (75 till 99,97) can be determined for 1-, 8-, and 24-hour averages. It has a flexible input of emission scenarios, i.e. effects of hourly, daily, weekly or seasonal fluctuations in emissions can be investigated. Changes in concentrations due to chemical reactions have also been incorporated. The dispersion and deposition of radioactive material is included. To this purpose the model has been extended with a special module assessing the decay of radioactive elements during transport. Results can be displayed in several ways (contourplots or line diagrams). As an example we give below a two-dimensional contourplot (see figure 4).

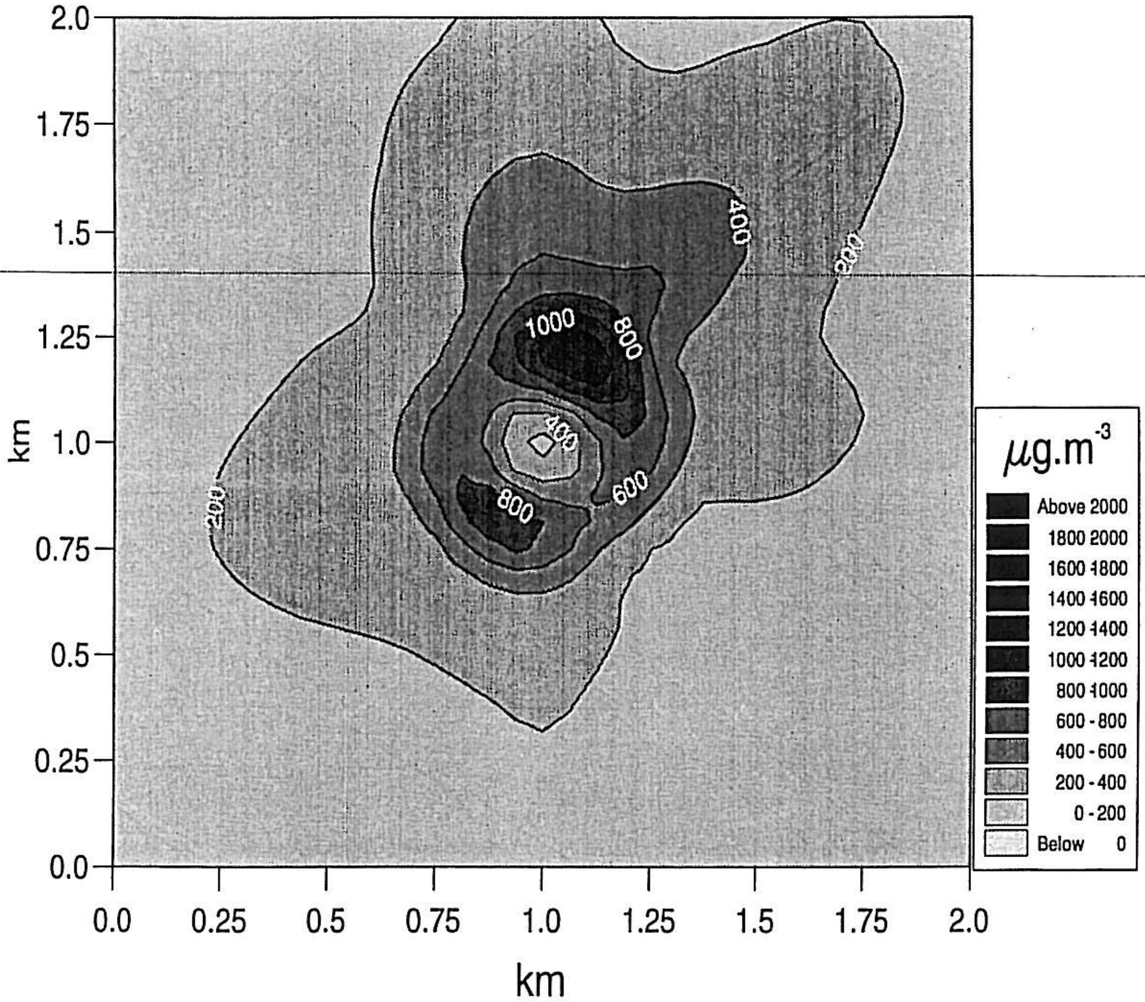

Figure 4. An example of a two-dimensional contourplot

On commercial basis a personal computer version (PC-STACKS for Windows) is available.

REFERENCES

[1] S.R. Hanna, G.A. Briggs and R.P. Hosker, Jr., 1982: Handbook on atmospheric diffusion, Atmospheric Turbulence and Diffusion laboratory, National Oceanic and Atmospheric Administration, DOE, USA.

[2] J.S. Irwin, 1982 Estimating plume dispersion - a comparison of several sigma schemes, J. Climate Appl. Meteor. 22, 92-114.

[3] J.J. Erbrink, 1995: Turbulent diffusion from tall stacks; the use of advanced meteorological parameters in the gaussian dispersion model STACKS, Thesis Vrije Universiteit, Amsterdam.

[4] M.L. Barad, 1958: Project Prairie Grass, a field program in diffusion, vol.1 . In: Geophysics researsch Paper, no.59.

[5] R.D.A. Scholten, H.C. Tieben and E.P. Weijers, 1995: Validation of STACKS with the Prairie Grass and LAMPF experiment (in Dutch).

[6] J.J. Erbrink, 1997: Revision National Model, Document prepared for the Ministry of Housing, Spatial Planning and the Environment, The Hague, The Netherlands.