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Short Contribution

On the reliability of CALPUFF and AUSTAL 2000 modeling systems regarding smoke and vapor plume mergence

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Abstract— Observations at power plants have shown that smoke plumes from stacks frequently merge with vapor plumes from cooling towers. Wind speed and direction play a key role in merging vapor and smoke plume. Mergence of stack and cooling tower plume leads to formation of undesirable substances such as sulfuric acid aerosols, acid mist, and acid fly ash. The present study shows that smoke and vapor plume mergence is a common phenomenon in Mátra power plant in Hungary; however more studies must be conducted in the future to reveal the type and number of plume mergence in the mentioned plant. The present work also indicates that the CALPUFF and AUSTAL 2000 modeling systems cannot provide enough information with regard to vapor and smoke plume mergence.

Key-words: smoke, vapor, wind, Mátra plant, CALPUFF, AUSTAL 2000

1. Introduction

Cooling towers eliminate heat from condenser cooling water by evaporation and reject this heat to the air in the form of a hot and humid plume. Cooling tower plumes consist of water vapor saturated air and liquid water in the form of suspended droplets. The emissions from stacks of fossil-fueled plants are primarily sulfur oxides and nitrogen oxides in addition to the usual constituents CO_2, N_2, O_2, and particulates such as fly ash and trace elements. Vapor plumes from the cooling tower of a power plant are similar in most respects to smoke plumes from the stack; however, the size difference is very great (*USEPA,* 1979).

2. Discussion

The potential effects of cooling tower and stack plume mergence include enhanced sulfate production and the ensuing production of undesirable substances such as sulfuric acid aerosols, acid mist, and acid fly ash. These interaction products may be generated from reactions involving sulfur dioxide and fly ash in stack plume with water vapor or water droplets contained in cooling tower plume. It should be pointed out that aerosols which are mentioned above refer to the dispersion of solid or liquid particles of microscopic size in gaseous media such as dust, smoke, or mist (*Rao* and *Rao,* 1989).

The results of smoke and vapor plume mergence could manifest itself in three ways as follows (*Knudson,* 1979):

1. Mist carried to the ground (subsequent to mergence with smoke plume) could have a lower pH due to dissolved acid sulfates.
2. Evaporation of mist (subsequent to plume mergence) could release dissolved sulfate aerosols resulting in the enhancement of plume sulfate levels.
3. Smoke plume sulfate levels could be enhanced due to the presence of water (vapor and droplets) associated with cooling tower plume.

Wind speed and direction play a key role in merging cooling tower and stack plumes. Therefore, wind rose at plant location should be used in determining the relative location of cooling tower with respect to stack when establishing plant arrangement and layout (*USEPA,* 1979).

Shalkouhi et al. (2017) reported that most of the studies with regard to stack and cooling tower plume mergence are dated back to the 70s and 80s. For example, *Kramer et al.* (1976), *Knudson* (1979), and *Haman* and *Malinowski* (1989) found that stack plumes frequently merge with cooling tower plumes in power plants.

There are multiple methods for determination of stack and/or cooling tower plume properties. One of these methods is uding a dispersion model like the *CALPUFF modeling system* (2011). Before 2011, the CALPUFF modeling system has been widely used for prediction of smoke plume properties only. For example, *Protonotariou et al.* (2005) reported that the overall performance of the CALPUFF modeling system was satisfactory. It must be pointed out that model evaluation studies involve selecting appropriate metrics or diagnostics (parameters summarizing key aspects of the behavior of a model) showing that the model can predict the metrics with appropriate accuracy compared with observations (*Fisher et al.,* 2015). In 2011, U.S.EPA included the ability of calculation of vapor plume in version 6 of the CALPUFF modeling system. Nevertheless, the CALPUFF modeling system cannot provide enough information about smoke and vapor plume mergence, considering the following argument:

As can be seen in *Fig. 1 Sarma* (1973) classified stack and cooling tower plume mergence into three different types. In the first type, the cooling tower plume mixes with the stack plume. In the second type, the stack plume mixes with the cooling tower plume. In the third type, both plumes spread more or less in parallel and merge at some distance away from their sources. For example, *Knudson* (1979) reported the first and second type, while *Dittenhoefer* and *de Pena* (1978), *Haman* and *Malinowski* (1989), and *Kramer et al.* (1976) revealed the third type (see *Table 1*).

Table1: Studies on different types of smoke and vapor plume mergences

Author/Authors	**First type**	**Second type**	**Third type**
Haman and *Malinowski* (1989)			√
Knudson (1979)	√	√	
Dittenhoefer and *Pena* (1978)			√
Kramer et al. (1976)			√

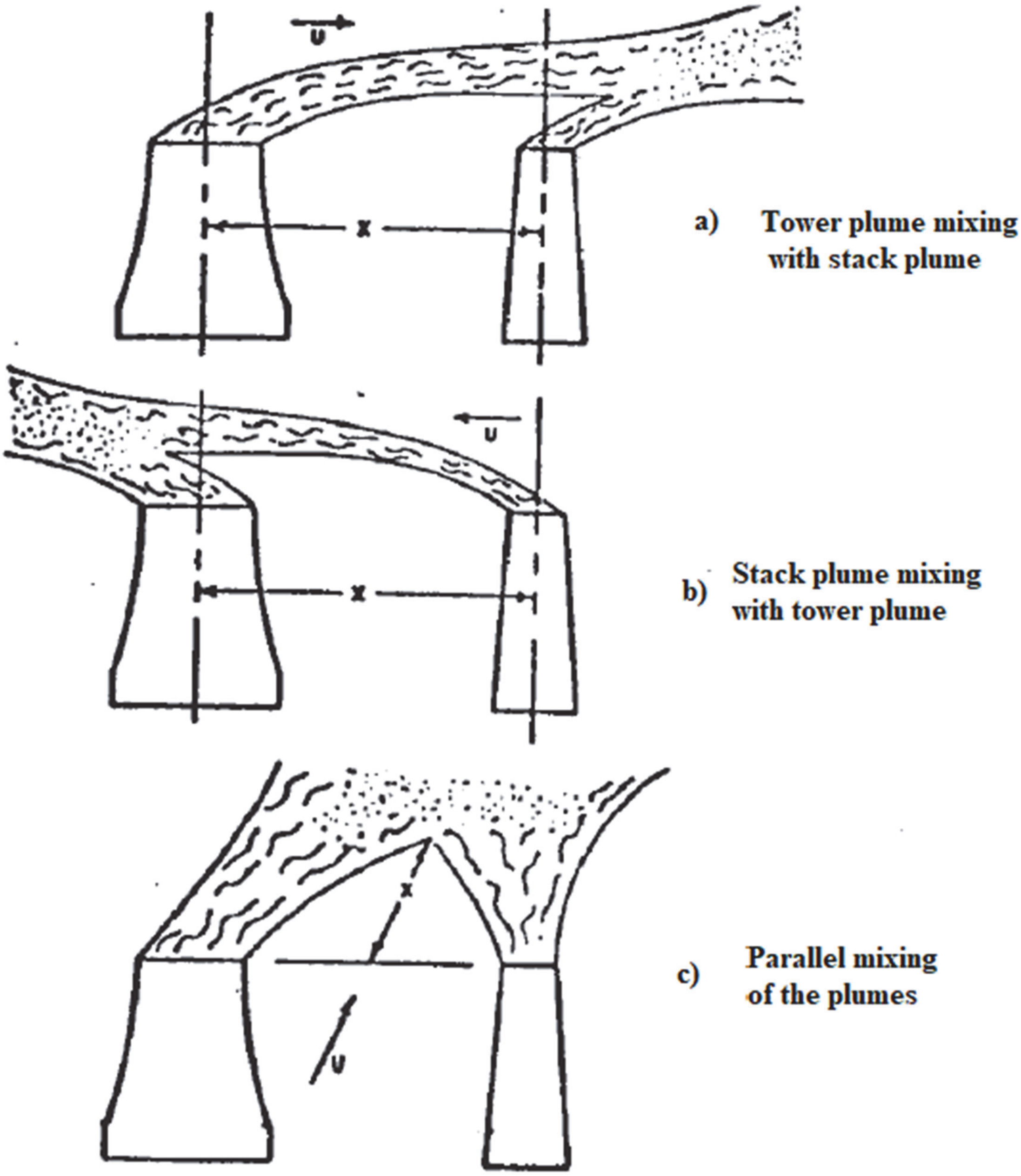

Fig.1. Different types of smoke and vapor plume mergence (*Sarma,* 1973).

In the first and second type, the plume height and length play an important role in merging the two plumes; while in the third type, the plume radius plays a key role in merging the two plumes (see *Fig. 2*).

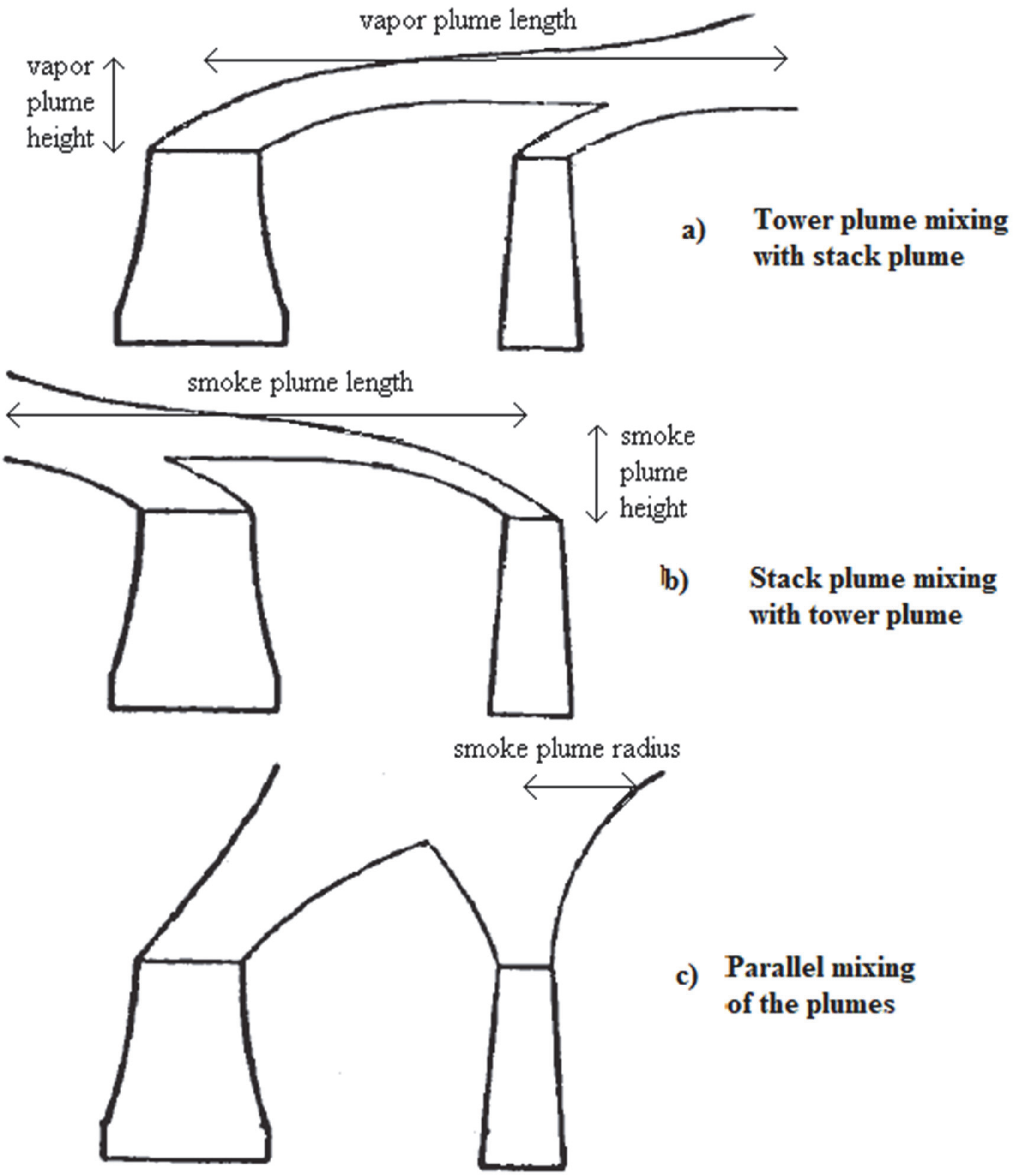

Fig. 2. Length, height, and radius of smoke and vapor plumes.

Moreover, in the CALPUFF modeling system, the momentum and buoyancy are treated according to the plume rise equations of Briggs (*Code of Federal Regulations,* 2009). These equations can be written as follows (*U.S. Materials Management Service,* 1985).

For unstable or neutral atmospheric conditions, the downwind distance of final plume rise is

$$xf = 3.5x^{*}, \tag{1}$$

where

$$x^{*} = 14F^{\frac{5}{8}}, \text{ when } F < 55 \ m^4 s^{-3},$$

$$x^{*} = 34F^{\frac{2}{5}}, \text{ when } F \geq 55 \ m^4 s^{-3}. \tag{2}$$

The final plume rise under these conditions is

$$\Delta h = 1.6F^{\frac{1}{3}}\left(3.5x^{*}\right)^{\frac{2}{3}} u^{-1}. \tag{3}$$

For stable atmospheric conditions, the downwind distance of final plume rise is

$$xf = \pi \ u \ s^{\frac{-1}{2}}, \tag{4}$$

where

$$s = g\frac{\partial \theta}{\partial z}T^{-1}. \tag{5}$$

The plume rise is

$$\Delta h = 2.6\left[F/\left(u \ s\right)\right]^{\frac{1}{3}}, \text{ for windy conditions,} \tag{6}$$

$$\Delta h = 5F^{\frac{1}{4}}s^{\frac{-3}{8}}, \text{ for near-calm conditions.} \tag{7}$$

In the above equations, g is the gravitational acceleration (ms^{-2}), d is the stack inside diameter at the top (m), F is the buoyancy flax parameter $\left[g \ v_s\left(\frac{d}{2}\right)^2\left(\frac{T_s - T}{T_s}\right)\right]$ (m^4s^{-3}), x^* is the distance at which atmospheric turbulence begins to dominate the entrainment (m), Δh is the plume rise above the stack top (m), x is the downwind distance from the source (m), T is the ambient air temperature (°k), Ts is the stack gas temperature (°k), u is the mean wind speed from the stack top to the plume top (ms^{-1}), v_s is the stack gas exit velocity (ms^{-1}),

$\partial\theta/\partial z$ is the vertical potential temperature gradient from the stack top to the plume top (°k m^{-1}), and *s* is the restoring acceleration per unit vertical displacement for adiabatic motion in the atmosphere, a stability parameter (s^{-2}).

The above equations do not include "smoke plume radius" as a predictor variable. On the other hand, in the CALPUFF modeling system, the vapor plume dimension is calculated by a processor named CTEMISS. There is no information in the literature which equation (e.g., *Hanna* (1976) or the other ones) is included in the CTEMISS. Among the vapor plume dimensions (height, length, and radius) only the height and length are computed by this processor; therefore, it can be stated that the CALPUFF modeling system is only valid for the first and second types of smoke and vapor plume mergences (see *Table 2*). Moreover, the radius of the plumes can also change change from time to time.

Table 2: The CALPUFF and AUSTAL 2000 modeling systems with regard to different types of smoke and vapor plume mergences

Model/Software	**First type**	**Second type**	**Third type**
CALPUFF	Valid	Valid	Invalid
AUSTAL 2000	Valid	Valid	Invalid

Another method for determination of smoke and/or vapor plume properties is using the *AUSTAL 2000* (2009) modeling system. Plume rise in connection with the discharge of exhaust by stacks is parametrically calculated according to the VDI 3782 Standard for Gaussian plume models. Also, plume rise of exhaust released by cooling towers is parametrically calculated according to VDI 3784 Standards for dispersions of natural-draft wet cooling emissions. There is no information in the literature which equations are included in the mentioned guidelines. Whereas among the smoke and vapor plume dimensions (height, length, and radius) only the height and length of smoke and vapor plumes are computed by the model, it can be stated that the AUSTAL 2000 is valid only for the first and second types of plume mergences, too.

Therefore, as indicated in *Table 3*, in order to investigate the third type of plume mergence, it is recommended to use other methods (e.g., satellite, airplane, and so on) instead of the CALPUFF and AUSTAL 2000 modeling systems. For example, *Dittenhoefer* and *de Pena* (1978) observed the third type of smoke and vapor plume mergences from an airplane. Also, *Staylor* (1978) determined smoke plume radius from satellite imagery. *Pettyjohn* and *Mckeon* (1976) reported that satellite imagery provides a convenient and inexpensive means for monitoring smoke plumes.

Table 3: The ability of the CALPUFF and AUSTAL 2000 models and some other methods with regard to smoke and vapor plume dimension

Model/Method	**Plume height**	**Plume length**	**Plume radius**
CALPUFF	Valid	Valid	Invalid
AUSTAL 2000	Valid	Valid	Invalid
Satellite, airplane, etc	Valid	Valid	Valid

Overall, it can be stated that to cover all types of smoke and vapor plume mergences, plume radius as a predictor variable must be included in the CALPUFF and/or AUSTAL 2000 modeling systems.

2.1. Study area

In this section, smoke and vapor plume mergences are investigated in a real environment. *Fig. 3* shows the first type of smoke and vapor plume mergence pictured over the Mátra Power Plant, Hungary. As can be seen in the figure, the wind direction of WSW (west-southwest) causes this type of plume mergence. *Fig. 4* indicates the second type of vapor and smoke plume mergence in the mentioned plant. As shown in the figure, the wind direction of ENE (east-northeast) causes this type of plume mergence. It must be stated that other wind directions can cause the third type of plume mergence the Mátra plant.

Fig.3. First type of plume mergence in the Mátra Power Plant, Hungary.

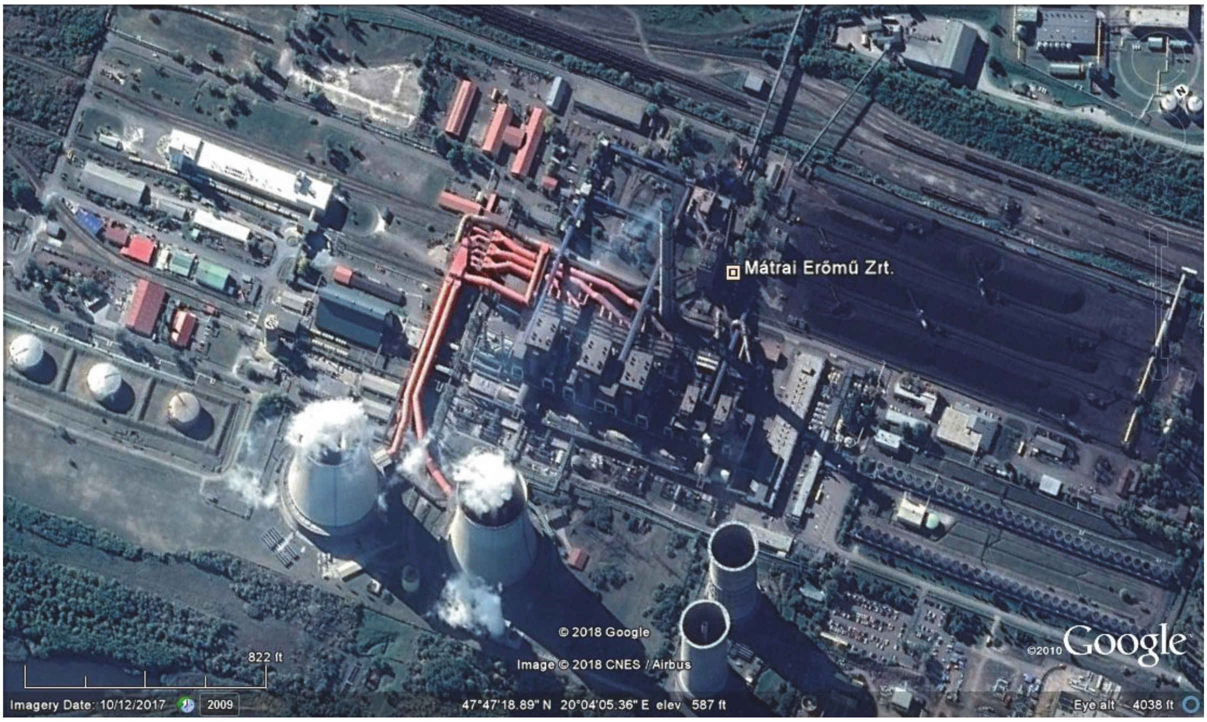

Fig. 4. Second type of plume mergence in the Mátra Power Plant, Hungary.

In addition to wind speed and direction, a little distance between the stack and cooling towers in the Mátra plant plays an important role in merging smoke and vapor plumes. This distance is only about 370 meters (see *Fig. 4*). In contrast, *Knudson'*s (1979) results revealed that smoke and vapor plume mergence is a common phenomenon in a power plant in U.S.A., where the distance between stacks and cooling towers was about 1000 meters.

According to *Fig. 5*, the distance between the Mátra plant and the surrounding cities varies from 3–15 kilometers. Whereas up to 50 kilometers from emission sources is considered as near field in air pollution, the first type of plume mergence can affect Visonta city, the second type of plume mergence can affect Vécs city, and the third type of plume mergence can affect the other cities.

Therefore, for investigating the number of the first and second types of plume mergences in the Mátra plant in the future, it is recommended to use the CALPUFF and/or AUSTAL 2000 modeling systems. Also, for investigating the third type of plume mergences in the mentioned plant in the future, it is recommended to use satellite, airplane, etc observations.

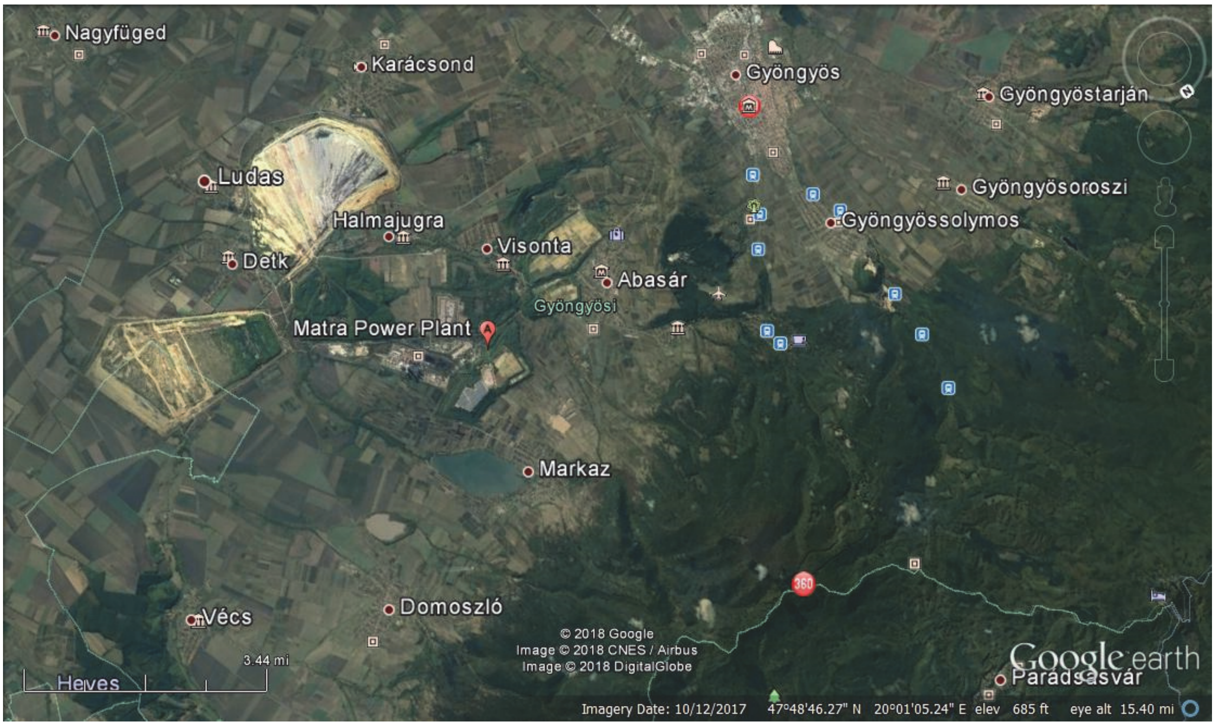

Fig.5. The Mátra Power Plant and the surrounding cities.

3. Conclusions

The results of the present study showed that smoke and vapor plume mergence is a common phenomenon in the Mátra Power Plant in Hungary; however, more studies must be conducted in the future to reveal the type and number of plume mergences in the mentioned plant. The results also showed that the CALPUFF and AUSTAL 2000 modeling systems cannot provide enough information with regard to vapor and smoke plume mergences.

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