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Inspecting smokestacks by IR thermographic surveying and heat conduction modeling

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ABSTRACT

The paper summarizes the authors' experience in conducting IR thermographic surveys of 60-200 m tall smokestacks typical of Russian power plants and industrial enterprises.

Keywords: IR thermography, inspection, smokestack, heat conduction, air leak

1. INTRODUCTION

The first attempts to use IR thermography in surveying smokestacks were made in Russia in the 1980s. However, the inferior quality of domestic IR cameras and a lack of motivation made the research fragmentary. By 2000, the need foe a quick and reliable smokestack inspection technique arose due to the fact that many smokestacks built in the 1960s have now exceeded their life expectancy and must be carefully checked for possible defects. In addition several manufacturers have recently switched fuels from coal to a cheaper gas, thus causing significant, unexpected and unfavorable changes in the condition of their smokestacks. In 1998, the United Power Networks of Russia, Inc., the major producer of electrical power in the country, allowed the use of IR thermography along with a traditional visual survey for the inspection of smokestacks. Since that time, the market for practical surveys and related research has grown constantly.

At Tomsk Polytechnic University, we have been using a succession of IR cameras for predictive maintenance since 1982. Until recently, the largest application area was the inspection of residential buildings. However, already in 2000, we have inspected more than 20 smokestacks. The surveys were targeted toward: 1) better understanding of visual observations that were reported by the staff, 2) concluding whether smokestacks need immediate repair or can be safely used for an additional period of time, and 3) helping contractors and building companies to define the scope of a required repair.

IR surveys of smokestacks are conducted in cooperation with a regional company called "Sibtechenergo" that specializes in building smokestacks and performing periodic inspections. Very often, IR thermographic data is complemented by the results of other tests, such as visual inspection, concrete performance evaluation etc.

Smokestack construction drawings and performance parameters, such as gas temperature, are always used as input parameters for solving a respective inverse (ill-posed) heat transfer problem where smokestack structural deficiences are modeled in order to compare simulation results to experimental data. As a final inspection result, a map of significant defects is provided to a contractor.

2. TYPICAL SMOKESTACK DESIGN

In most cases, we encounter two types of smokestacks that use either bricks or reinforced concrete as a material for the external shell that bears the main load. Brick smokestacks are typically of a height from 40 to 100 m, while reinforced concrete ones can easily reach 200 m (the tallest one is 430 m). Smokestacks include an internal refractory (brick) layer, an air gap filled with mineral wool mats, and the external shell (see the sketch of a smokestack made of reinforced concrete in Fig. 1). The mostly uniform construction of a smokestack is disturbed by the so-called "tear-collection rows" intended for collecting the liquid that condenses on the internal surface (Fig. 1). As shown in the figure, tear-collection rows do not have

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the insulation layer of mineral wool. This results in a particular thermal pattern that may be observed thermographically from the outside.

In most cases, due to high gas velocity, the pressure inside a smokestack is lower than the outer one. Schematic presentations of the thermograms that are typical for both types of smokestacks are shown in Fig. 2. The external surface is always warmer than the ambient by few degrees Celcius with the temperature increasing from bottom to top. Hence, at any height, a smokestack can be characterized with a non-defect temperature T_{nd} , while structural defects cause either negative ($-\Delta T$) or positive ($+\Delta T$) perturbations. Brick smokestacks often suffer from long cracks where in-leaking air creates significant negative temperature signals (Fig. 2a). On the contrary, insulation deficiencies cause overheated areas to appear on the surface. The largest warm area usually occurs at the top of a smokestack where the thermal insulation is thin and the hot gas flowing out can envelop the upper part of a smokestack. In concrete smokestacks, the temperature pattern is more complicated. First of all, there are regularly spaced bands typically 2.5 m high seen from top to bottom. These areas correspond to transition seams from one concrete section to another. The quality of concrete can be technologically inferior in these seams and they typically look a little colder than surrounding because of a higher concrete porosity. Then, there are a few band-like warm areas on each concrete smokestack that correspond to tear-collection rows (Fig. 1) where the absence of mineral wool reduces thermal resistance. Also, the top of concrete smokestacks appear warmer as is true for brick ones. Finally, possible local defects, such as cracks and insulation deficiencies cause local temperature disturbances (Fig. 2b).

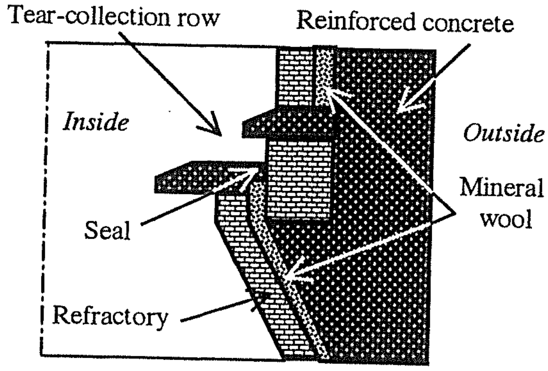


Fig. 1. Typical design of a reinforced concrete smokestack

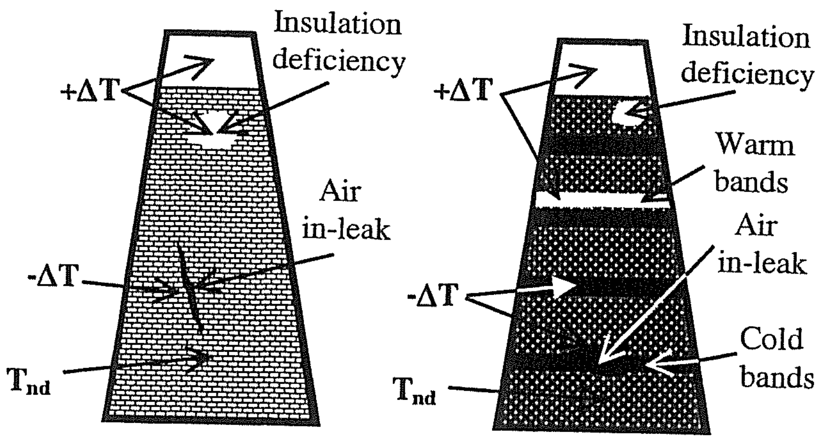


Fig. 2. Schematic presentation of typical smokestack thermograms:

a – brick smokestack,
b – reinforced concrete smokestack

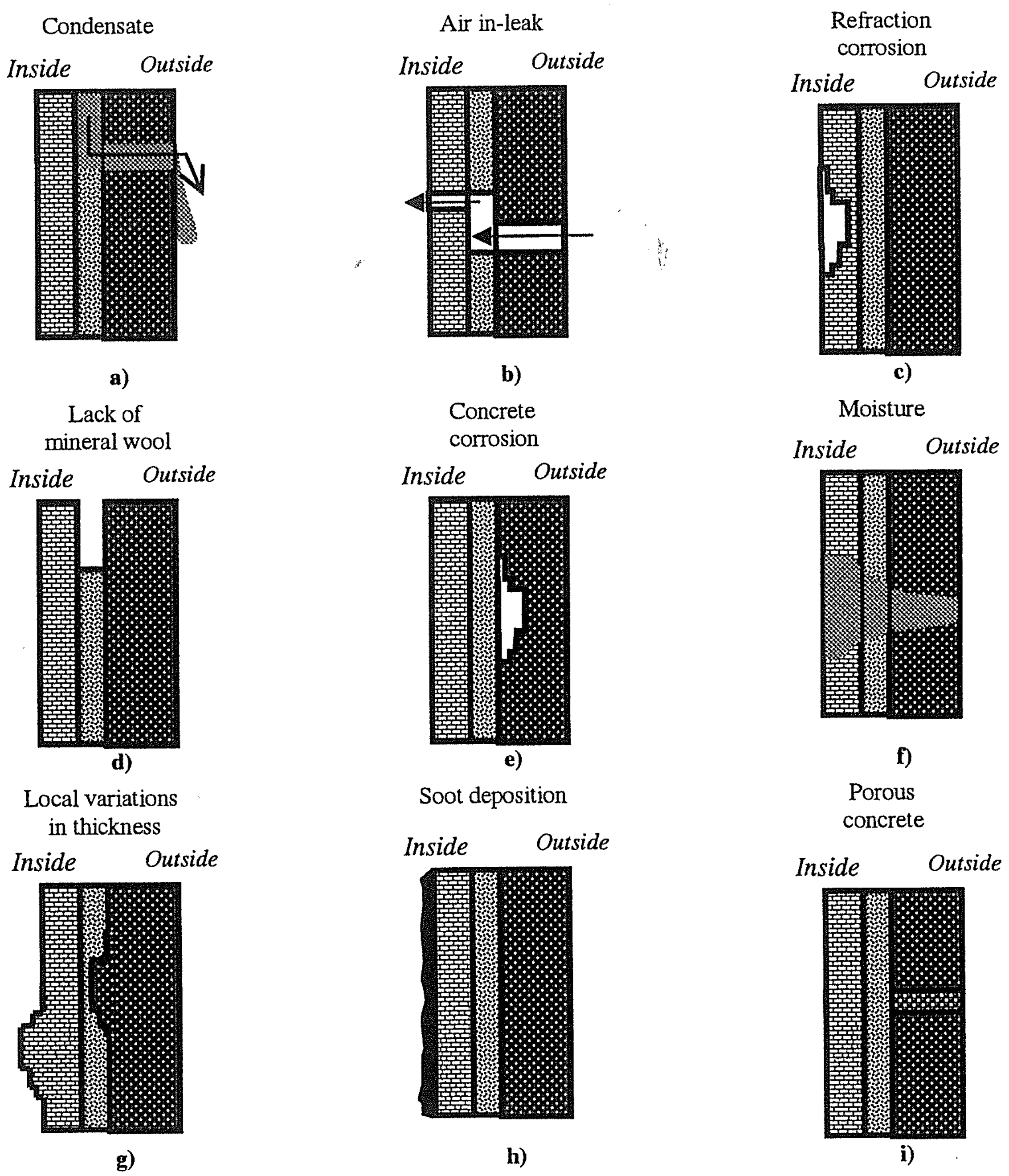


Fig. 3. Smokestack defect models

3. TYPICAL DEFECTS AND DECISION MAKING CRITERIA

Unlike the IR thermographic inspection of electrical joints, where temperature signals are rather high and defect classification is relatively simple, the interpretation of the results of smokestack inspection is more challenging. For example, in our case, on-site presentation of results to a customer often ends up with the following rule-of-thumb in regard to a smokestack quality: "Good" (temperature anomalies do not exceed 2°C), "Medium" (temperature anomalies between 2-5°C), and "Bad" (temperature anomalies exceed 5°C).

A more objective evaluation can be made by analyzing a relationship between surface temperature signals and smokestack structure. Physically, smokestack problems are very similar to those appearing in building inspection.

Some typical smokestack defects are shown in Fig.3. The defect physics is clear from the corresponding drawings. Most defects can be reduced to either insulation deficiencies or air in-leaks. These kinds of defects are considered in more details below.

3.1. Insulation deficiencies

Mathematically, the evaluation of insulation deficiencies is related to steady-state heat conduction through a plate (Fig.4a and Eq.(1)).

$$T_{out}^{w} = \frac{T_{in}^{a} + \alpha_{out}\, T_{out}^{a}\, (\dfrac{1}{\alpha_{in}} + R_t)}{1 + \dfrac{\alpha_{out}}{\alpha_{in}} + \alpha_{out}\, R_t}. \qquad (1)$$

Here: T_{out}^{w} - smokestack external surface temperature, T_{in}^{a} - gas temperature, T_{out}^{a} - ambient temperature, α_{in} - heat exchange coefficient on the smokestack internal surface, α_{out} - heat exchange coefficient on the smokestack external surface, R_t - smokestack wall thermal resistance.

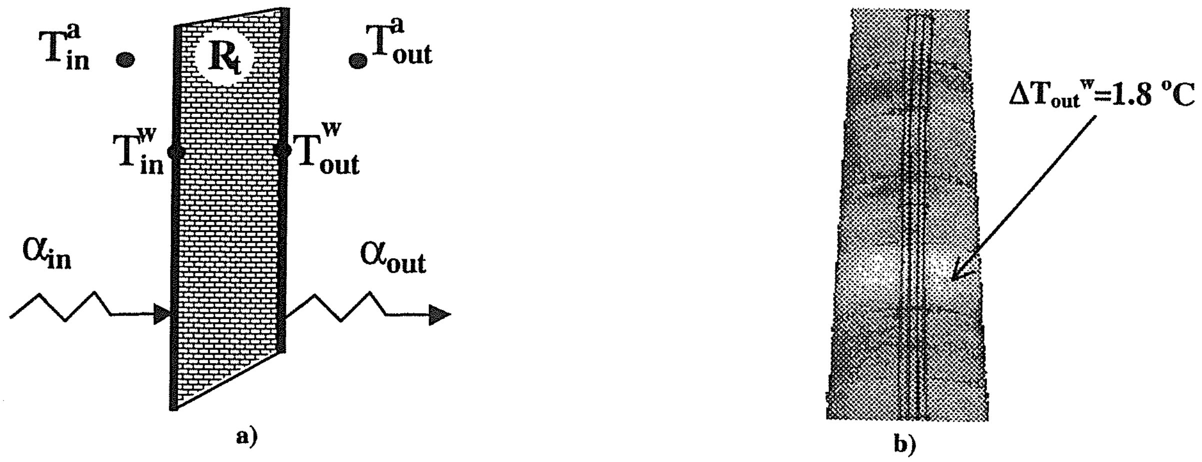


Fig.4. Heat conduction through a wall

The presence of structural defects leads to surface temperature signals $\Delta T_{out}^{w}\,(\Delta R_t)$. An absolute R_t value should be determined by inverting Eq.(1) (see also [1]):

$$R_t = \frac{T_{in}^{a} - \dfrac{\alpha_{out}}{\alpha_{in}}(T_{out}^{w} - T_{out}^{a}) - T_{out}^{w}}{\alpha_{out}\,(T_{out}^{w} - T_{out}^{a})}. \qquad (2)$$

Eq. (4) presumes that an R_t value is approximately known from the drawings, and ΔT_{out}^{w} is measured with an IR imager. A magnitude of ΔR_t is much more stable compared to variations in the involved parameters. For instance, using the approach by Eq. (3), it can be shown that all variations of the parameters from Table 1 result in the inaccuracy $\Delta(\Delta R_t) \approx 0.019\ m^2\ K W^{-1}$ that is equivalent to $\Delta T_{out}^{w} = 0.059\ {}^oC$. Assuming that the threshold temperature resolution of an IR imager is $0.1\ {}^oC$, the sensitivity of such a differential technique to variations in thermal resistance is $\Delta R_t = 0.032\ m^2\ K W^{-1}$. This estimate allows the conclusion that the differential technique is capable of sensing minor structural changes within a smokestack.

The difference between determining an absolute R_t value and its increment ΔR_t can be well illustrated with the analogous situation that appears in infrared radiometry where absolute temperatures can be hardly measured with an accuracy better than $1-3^o C$ but temperature variations are easily estimated at a level of $0.1\ {}^oC$.

The example of applying Eq. (4) to experimental data is shown in Fig. 4b. A brick smokestack consisted of two (0.51 m and 0.12 m) brick layers separated by the 0.05 m-thick air gap has revealed a vast warm area characterized by $\Delta T_{out}^{w} = 1.8\ {}^oC$ (see Fig. 4b). The total wall thermal resistance was accepted as

$$R_t = \frac{0.51 m}{0.76\ W m^{-1} K^{-1}} + \frac{0.12 m}{0.76\ W m^{-1} K^{-1}} + 0.15\ m^2\ K W^{-1} = 0.98\ m^2\ K W^{-1}.$$

Here $K = 0.76\ W m^{-1} K^{-1}$ is the thermal conductivity of brick and $R_t = 0.15\ m^2\ K W^{-1}$ is the recommended thermal resistance of an 0.05 m-thick air gap. The ambient temperatures were respectively: $T_{out}^{a} = 17\ {}^oC$ and $T_{in}^{a} = 120\ {}^oC$. The heat exchange coefficients have been accepted as $h_{in} = 23\ W m^{-2} K^{-1}$ and $h_{out} = 16\ W m^{-2} K^{-1}$. By substituting all these input parameters in Eq. (4), we obtain that the possible reduction of thermal resistance in the detected defect area is $\Delta R_t = 0.33\ m^2\ K\ W^{-1}$ that can be explained by the destruction of both the internal brick layer and the air gap ($R_t = \dfrac{0.12 m}{0.76\ W m^{-1} K^{-1}} + 0.15\ m^2\ K W^{-1} = 0.31\ m^2\ K W^{-1}$.

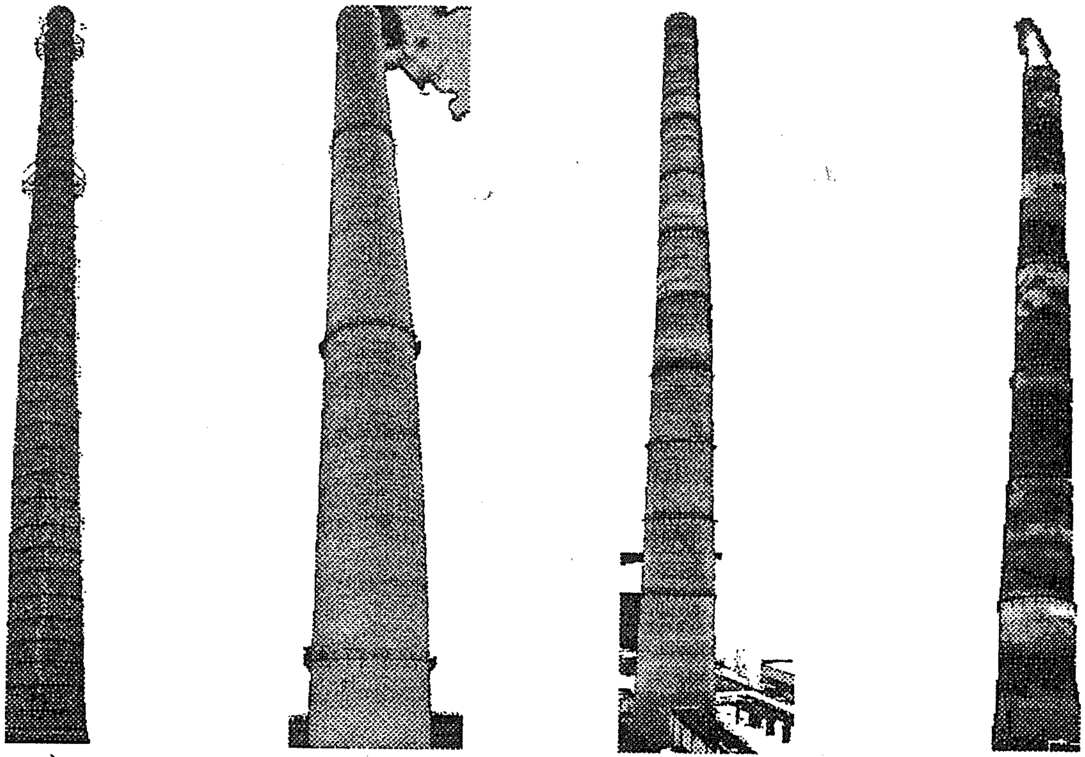
3.2. Air in-leaks

The detailed analysis of how an air leak rate can be determined by the surface temperature of the leak 'footprint' is still to be done. Here we limit ourselves with the simplified model that follows from the corresponding classical steady-state solution.

Let us assume that an air leak occurs through a thin crack of whose the visible size is H and the total depth is L (Fig. 5a). The heat power carried by the air flow through the defect is

$$q = C^{air} \rho^{air}\ P\,(T_{in}^{a} - T_{out}^{a})\ [W], \qquad (5)$$

where C^{air}, ρ^{air} are the specific heat and density of air, and P is the leak rate in [$m^3\ s^{-1}$]. By each side of the defect, this heat power creates the temperature gradient equal to:



a) b) c) d)

Fig. 6. Examples of smokestack inspection results:

a – visual image,
b – panoramic IR image, "Good"
c – panoramic IR image, "Medium",
d – panoramic IR image, "Bad"

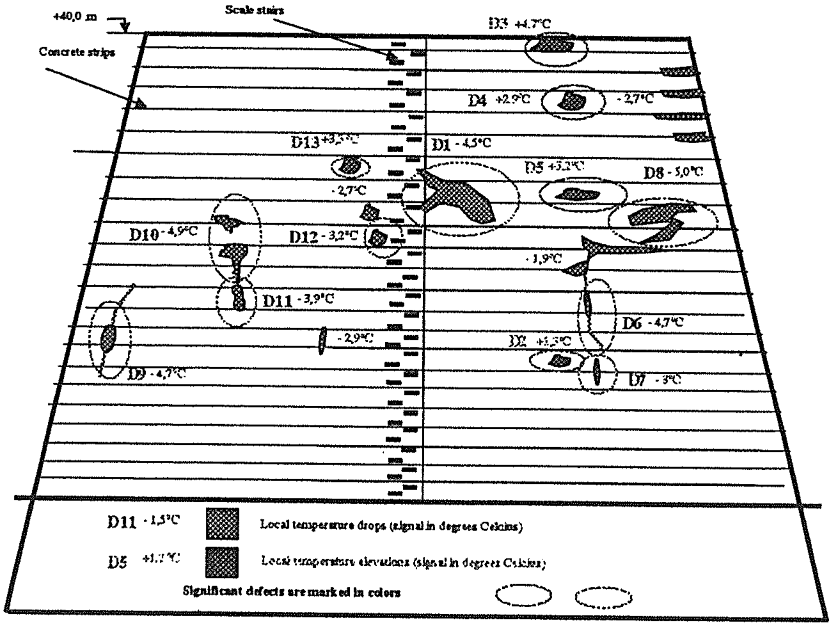


Fig. 7. Smokestack defect map

Fig. 6c, also recently repaired, however, revealed few suspicious areas that probably reflected a low quality of the repair work. Finally, the image in Fig. 6d depicts the smokestack of a bad quality that is proved by the presence of multiple overheated areas, many of which were regarded as a loose of insulation properties by mineral wool mats.

Each particular thermogram is evaluated according to the criteria described in Section 3 to create a defect map that contains only those defects that are regarded as dangerous or at least worth to be discussed with the contractor. The example of a defect map is given in Fig. 7. Insulation deficiencies are shown in red as the areas of elevated temperature and air in-leaks are shown in blue as the areas of lower temperature. Such a defect map is typically provided to a contractor in order to facilitate decision making.

5. CONCLUSION

The IR thermographic inspection of smokestacks is an interesting scientific enterprise of great practical importance. It is both theoretically challenging and physically dangerous. From the academic point of view, IR smokestack inspection is a good example of a practical problem where the thermal properties of the materials involved and the dimensional information on the inspection subject are rarely available and must be assumed. The lack of this data makes the development of a good quantitative theoretical analysis evaluation of smokestack inspection a difficult task. However, the smokestack owners are usually satisfied with qualitative information only; they are only interested in knowing what repairs are necessary and whether the smokestack can remain in service.

6. ACKNOWLEDGMENT

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