

# Design optimization study for an infrared heater using CFD and sensitivity analysis

**Citation for published version (APA):**

Hojer, O., Basta, J., & Hensen, J. L. M. (2007). Design optimization study for an infrared heater using CFD and sensitivity analysis. In O. Seppänen, & J. Säteri (Eds.), *Proceedings of the SCANVAC Roomvent 2007 Conference, 13-15 June 2007, Helsinki, Finland* (pp. 9-pages). FINVAC.

**Document status and date:**

Published: 01/01/2007

**Document Version:**

Accepted manuscript including changes made at the peer-review stage

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

**Take down policy**

If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

## **Design optimization study for an infrared heater using CFD and sensitivity analysis**

Ondrej Hojer<sup>1</sup>, Jiri Basta<sup>1</sup>, Jan Hensen<sup>2</sup>

<sup>1</sup>Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Environmental Engineering

<sup>2</sup>Building Physics & Systems, Technische Universiteit Eindhoven

*Corresponding email: Ondrej.Hojer@fs.cvut.cz*

### **SUMMARY**

Sensitivity analysis (SA) has become a very popular technique for various application areas. However, not many studies concern SA using CFD (computational fluid dynamics). The main problem appears to be the large number of model executions when using the Monte Carlo method of SA. The computing resources and time needed for such a SA in combination with CFD (in which one model execution could take several hours) can be enormous. Nevertheless, this paper describes an approach of using SA in such cases. The recommendations are obvious: simplifying the model as much as possible; considering just a key part of the model; and take more care about the speed of convergence. On this basis a case study on “Optimization of gas infrared heater radiation geometry” has been performed. The most interesting result is that the shape of the heater and the reflector material do not significantly influence the heat delivery to the occupied zone. The main conclusion is that Monte Carlo sensitivity analysis is not suitable for large CFD models with low level of abstraction. In order to obtain good results, we recommend to select a smaller part of the overall domain and/or to significantly simplify it.

### **INTRODUCTION**

Nowadays, great attention is paid to residential and commercial buildings and systems. Buildings are tighter, better insulated, HVAC systems have very often smart control and also efficiencies of the devices are very high. Heating energy demand per one square meter varies for that reason between 25 and 100 kWh/m<sup>2</sup>. Although this value is in industrial area even higher than 600 kWh/m<sup>2</sup>, any savings recommendations are mostly forgotten. It is obvious that potential for energy savings in this area is quite large. However, savings are not just about HVAC device as a separate element. Complete system always needs to be considered. Reduction of installed power output should be the primer goal. That was a key point for starting a study that should optimize medium intensity gas infrared heater and its radiation geometry. These devices are primarily used for heating of such a large space industrial buildings.

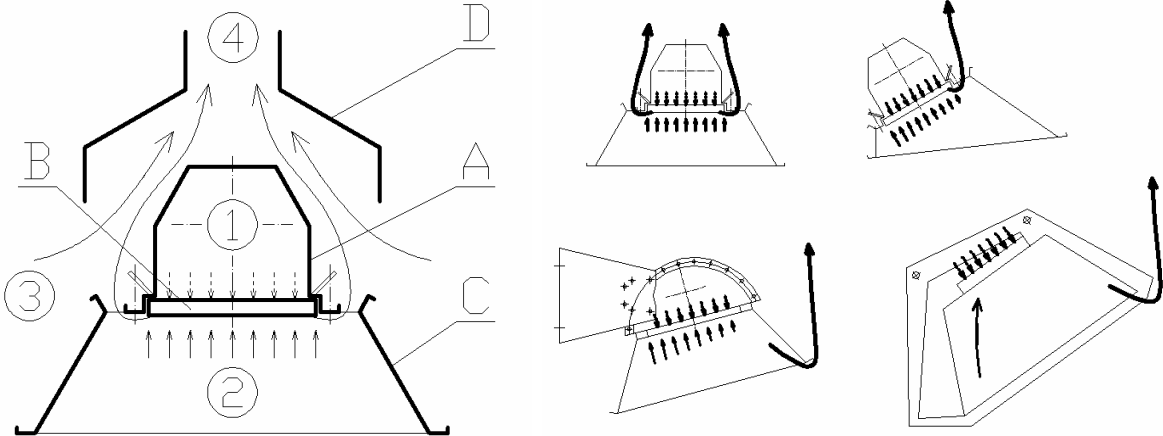
In this contribution, universal method of optimization is used and its applicability on heating of large industrial buildings with medium intensity gas infrared heaters is shown. The method is called sensitivity analysis (SA). A model of gas infrared heater within a simple room was made in CFD (Computational Fluid Dynamics) and for sensitivity analysis, SimLab software was chosen. The objective of this contribution is to describe and comment a method how SA,

in this case performed by SimLab software, can be used for CFD simulations and further point out most common problems on concrete example, optimization of medium intensity gas infrared heater radiation geometry.

**Medium intensity gas infrared heaters**

Construction of medium intensity gas infrared heater (MIGIH) (fig. 1) varies from case to case according to manufacturer, but main principles are always the same. Typical MIGIH consists of following parts: control unit, inlet nozzle, mixing chamber (A), ceramic plaques (B), and reflector (C). Some manufacturers add to their construction different improvements to increase radiation efficiency. For example, austenitic steel grid located in front of ceramic plaques. Austenitic steel has specific properties causing that more heat from burning gas is utilized into solids and is reradiated. Another example, insulation with top surface made of low-emissive (polished) metal is sometimes added to reflector to decrease heat losses by convection and backward radiation. Some heaters even preheat mixing chamber to increase temperature of mixture before burning and utilize more energy this way. However, because of complicacy of construction (hence higher price) there is a low number of such MIGIHs in operation. Medium intensity gas infrared heaters without energy utilization of combustion products prevail.

Function of typical heater is described also on fig. 1. Natural gas (or propane - butane) enters infrared heater through inlet nozzle where primary ambient air is by ejection effect soaked according to gas overpressure into the mixing chamber. Air is completely mixed with gas and created mixture (1) is, due to pressure conditions, evenly distributed to the ceramic plaque's surface. Then, mixture passes through these porous plaques and it is on their surface ignited by an electrode and burned with secondary air (2). Temperature of the burnt gas is very close to 900 °C (1650 °F), but it is quickly mixed with ambient air (3) and thus temperature is gradually decreasing. Anyway, burnt gas has still temperature high enough to create large rising flow of burnt gas and air (4). These flows are also shown for different constructions of infrared heater on the right side of fig 1.



**Fig. 1 Various types of medium intensity gas infrared heater**

To describe and/or compare different heater types specific terms are used [1]. Generated infrared energy divided by total energy input is called radiation-generating ratio. Similarly, fixture efficiency is an index of fixture's ability to emit the radiant energy developed by radiation source and in the end; pattern efficiency is an index of fixture's effectiveness in directing the infrared energy into a specific pattern. Most commonly used term is radiation-

generating ratio, sometimes called radiation efficiency. Radiation efficiency typically varies from 0.50 to 0.80. Some manufacturers even claim that the radiation efficiency of their medium intensity gas infrared heater is about 0.95. But, because in various sources can be found different definitions of radiation efficiency, you should always ask, how this efficiency is evaluated. Compare comparable values.

## METHODS

Optimization process was performed using advantages of sensitivity analysis (SA) [2]. It is widely known technique that has various applications. In general, it provides information about influences of independent input variables on dependent output variables. Sensitivity analysis actually specifies which input parameters are the most influential on the uncertainty of the output.

Before starting an optimization process, a theoretical model of examined element has to be described. CFD package Fluent [3] with preprocessor Gambit [4] was used for this purpose because of complexity of included physical laws. The essential point in such a combination with CFD is the choice of level of abstraction. If you describe the model too much in detail you probably will not be able to perform a sufficient amount of number of model executions as will be discussed later. On the other hand, inappropriate simplification can cause omitting of important parameters and hence it may significantly influence the results. However, reasonable simplifications are because of high computation cost welcome.

SimLab software [5] was developed for performing both uncertainty and sensitivity analyses. The heart of the SA implemented in this software is Monte Carlo technique. Therefore, both simple (internal) and more complex (external) models can be assessed. The technique consists of three parts, pre-processing, execution of a model and post-processing. In pre-processing phase, the sample of  $N$  rows and  $M$  columns is generated according to chosen sampling method and number of executions  $N$ . Thus, each column represents one input factor  $M_i$  and each row provides input factors for one model execution  $N_j$ .

### Input settings

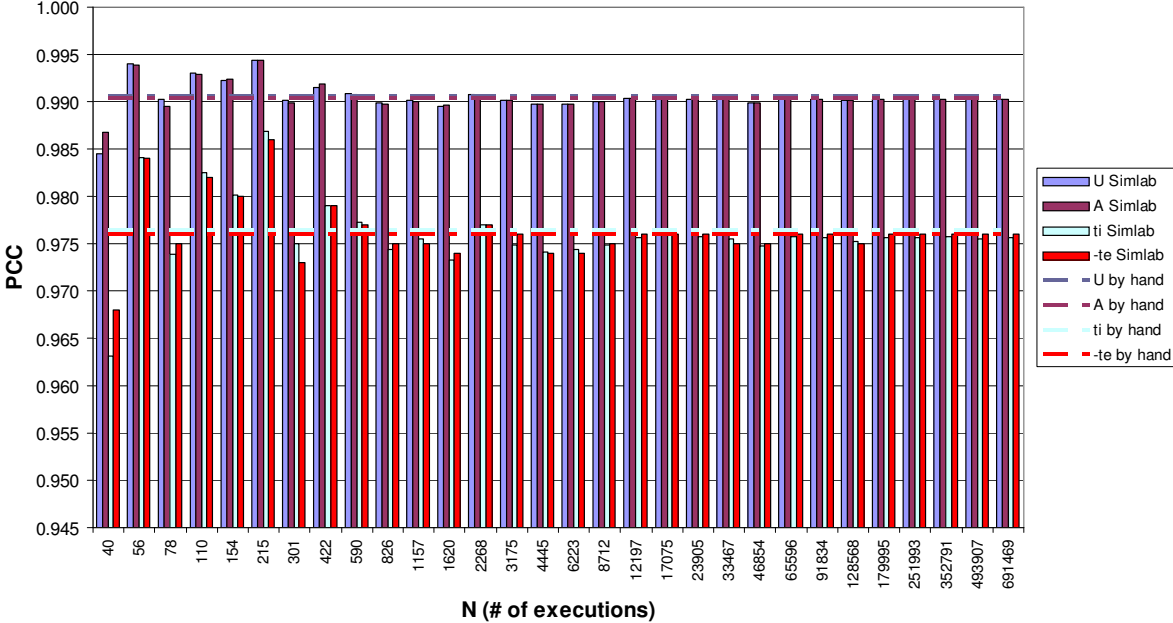
Many methods are available for generating a sample such as *Random*, *Latin hypercube*, *Morris*, *Sobol*, and so on. As an output, there are also various measures of sensitivity like *Pearson*, *Partial correlation* or *Standardized regression coefficient* and instead of these also their ranked versions. To find a most suitable combination of sampling methods, sensitivity measures and the number of execution, a small study on a simple model was performed as show figures 2 and 3. Settings were investigated on a simple (internal) model of a steady state heat transfer through the wall (equation 1),

$$Q = U \cdot A \cdot (t_i - t_e) \quad (1)$$

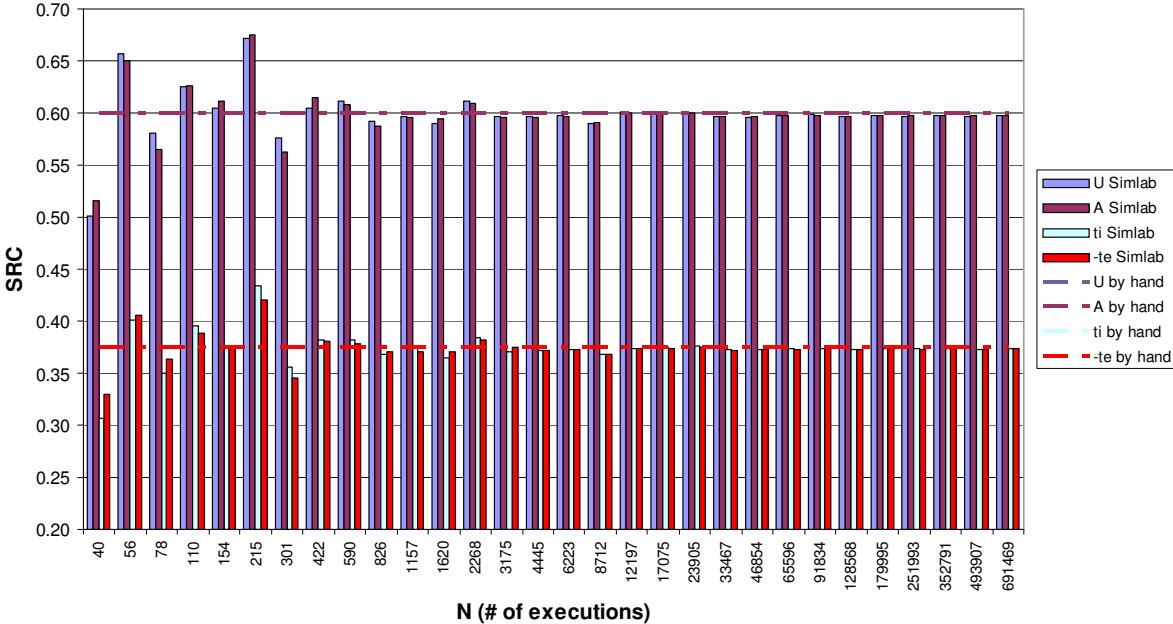
where

$Q$ [W]	transferred heat per unit of time;
$U$ [W/(m <sup>2</sup> K)]	overall heat transfer coefficient;
$A$ [m <sup>2</sup> ]	heat transfer area;
$t_i$ [°C]	internal temperature;
$t_e$ [°C]	external temperature.

The reason for such a simple model is a possibility of verification with by hand calculations. Absolute values were set to be representative for a real case, distributions were normal and standard deviations  $\sigma$  were set for all factors the same 5 % of the mean  $\mu$ .



**Fig. 2** Dependency of partial correlation coefficient (PCC) on number of executions (N)



**Fig. 3** Dependency of standardized regression coefficient (SRC) on number of executions (N)

From figures above, it is quite clear, that with increasing number of executions, the precision of the sensitivity indices is improving. This is backed up with very good agreement between values gained from SimLab and values calculated by hand. In order to get narrower scale on y-axis PCC and SRC values of  $t_e$  were multiplied by minus one. The most influential, as expected, in this simple case are overall heat transfer coefficient and heat transfer area. Next are both internal temperature and negative value of external temperature. Absolute values are

of course the same. To conclude, both PCCs and SRCs could be used for sensitivity measures, the rank of examined parameters is the same. The only influential factor is the number of executions.

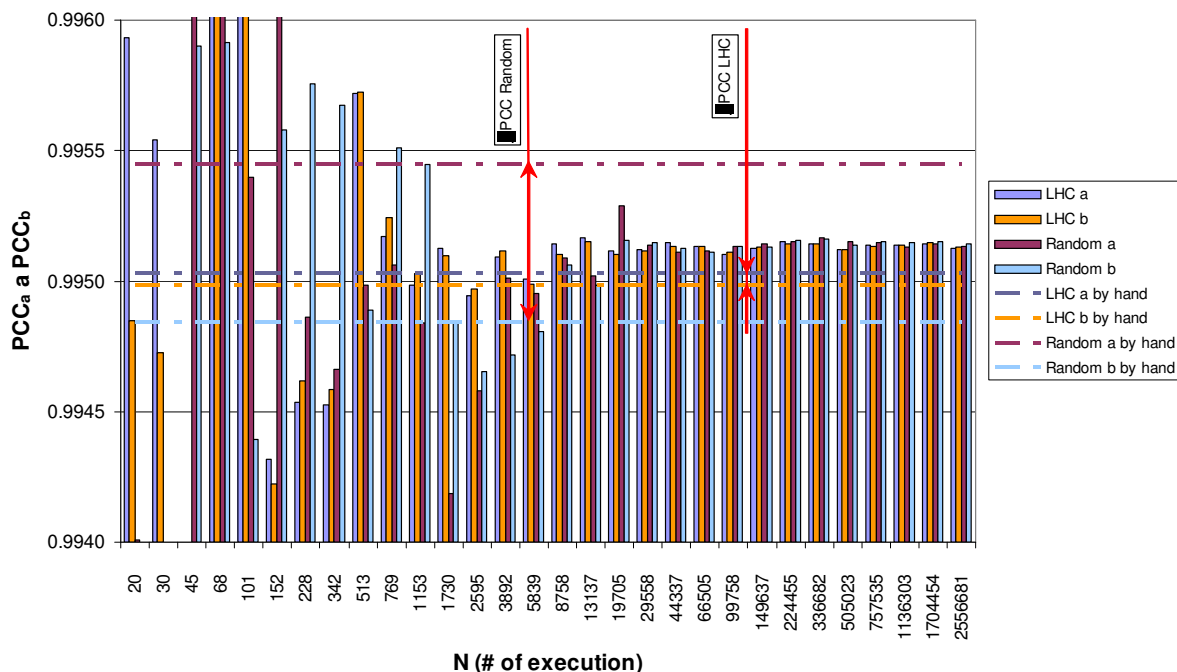
In the second part of the study was found that the Latin hypercube sampling gives more precise results than the other sampling methods (at least for normal distribution of all input factors). For this part, an example described with equation 2 was used:

$$y = a \cdot b, \quad (2)$$

where

$y [-]$  dependent output variable;  
 $a [-]$  independent input variable;  
 $b [-]$  independent input variable.

It is the simplest model that can be, but for assessing the differences between sampling methods is sufficient. These differences are apparently shown in fig. 4 between Latin hypercube and Random sampling. According to theoretical backgrounds both partial correlation coefficients for  $a$  and  $b$  should be the same. Therefore, the difference between them can be the measure of accuracy. The smaller is the difference the more accurate is the method. The reason why partial correlation coefficient computed by hand does not fit the data from SimLab is in chosen number of executions for “by hand” calculation, which was  $N = 1153$  (one of the columns in fig. 4). For sure with increasing number of the model executions increases preciseness of “by hand” calculations as well. Anyway, Latin hypercube offers obviously more precise results than the Random sampling method.

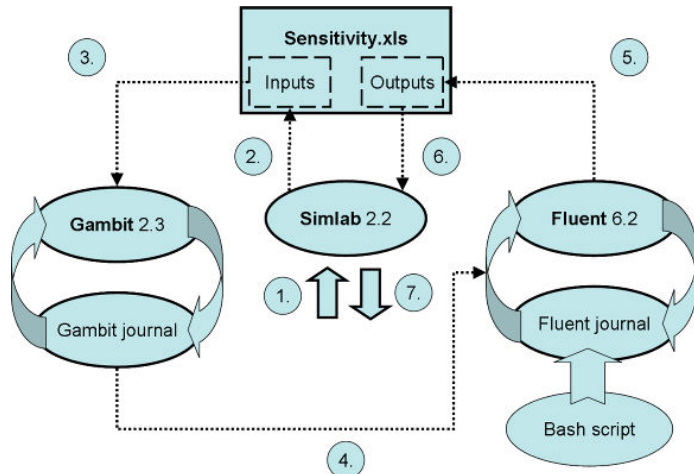


**Fig. 4 Differences in accuracy of LHC and Random sampling methods**

### Sensitivity analysis

In previous paragraph, basic recommendations were formulated in order to increase precision and reduce computation cost. Hereafter, whenever sampling method will be mentioned, Latin

hypercube is considered. Also assessing of sensitivity indices will be shown just on partial correlation coefficient because as it was mentioned above standardized regression coefficient has nearly the same predicative value. The ground of CFD model sensitivity analysis is in the interaction among included software. In our case was chosen SimLab, MS Excel, Gambit and Fluent.

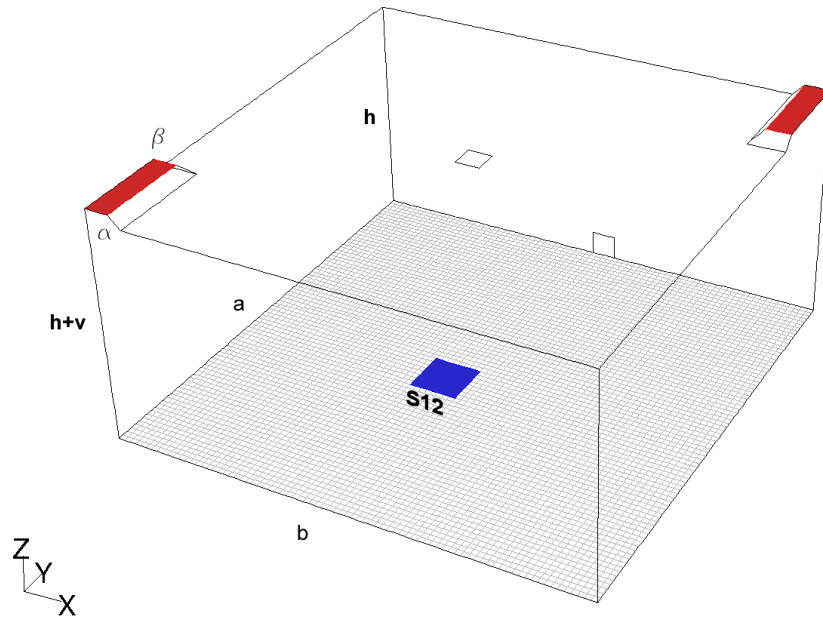


**Fig. 5 Scheme of practical application of SA with SimLab software to CFD model**

As it is shown on the fig. 5, an *Sensitivity.xls* is used as an exchange file. Whole procedure starts with generating a sample into Excel list called *Inputs* (2). Input factors influencing mesh are then copied into Gambit journal and the others into Fluent journal (3). Gambit is run and N input mesh files are created. Then all meshes are gradually loaded into Fluent (4) and after assigning related boundary conditions, simulation is commenced. Results are afterwards copied back into the Excel list called *Outputs* (5) and after saving and closing Excel, post-processing phase starts (6).

### Case study

In order to include all influencing input factors a model (fig. 6) was created. The model is represented with square shape room with variable dimensions  $a$  and  $b$ . At two top opposite corners, there are suspended two separate quarters of infrared heaters. Variable  $h$  represents a height of suspension and  $v$  is a depth of reflector. The reflector angle in  $x$  direction is  $\alpha$ , in  $y$  direction  $\beta$ . All of these factors had to be set into Gambit journal. To the second group of factors belong the temperature and the emissivity of radiant plaques  $T_d$ ,  $\varepsilon_d$ , the temperature and the emissivity of floor  $T_p$ ,  $\varepsilon_p$ , and the temperature and the emissivity of reflectors  $T_r$ ,  $\varepsilon_r$ .



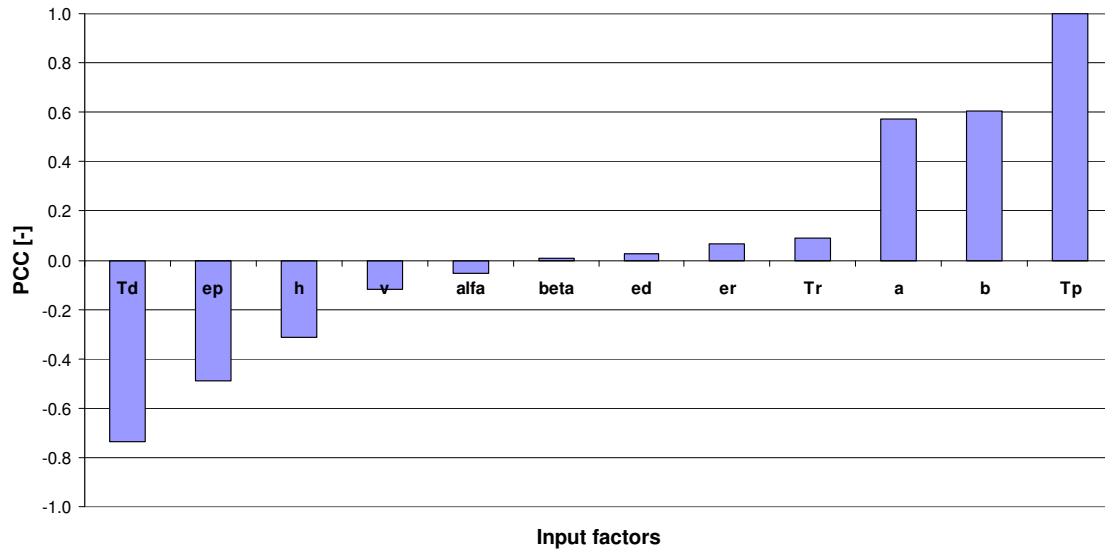
**Fig. 6 Scheme of examined model**

An objective of this sensitivity analysis is to find out which of these input factors or parameters are important when considering radiant heat transfer from infrared heaters to the floor surface S12. The output variable is incident radiant heat flux at the surface S12.

## RESULTS

After performing the uncertainty and sensitivity analysis, quite expected results were obtained. They are shown on partial correlation coefficients in fig. 7. The most influential are gradually temperature of the floor, temperature of radiant plaques, both dimensions of the room, emissivity of the floor and the height of suspension. On the other hand almost negligible are temperature of reflectors, depth of the reflectors, emissivity of reflectors, emissivity of radiant plaques and both reflector angles. Besides, important information results from fig 7. Theoretically, the increase in parameters of which the PCCs are above zero should cause the increase in the output. However, here it is different. Explanation is the negative value of output. Simply, the rule of proportion is opposite. For example, negative value in  $PCC_{T_d}$  means that increase in  $T_d$  causes increase in transferred radiant heat flux and so on. Practicing the same rule, when  $T_d$ ,  $e_p$ ,  $h, v$  and  $alfa$  are increased radiant heat flux incident at S12 increases as well, on the other side,  $beta$ ,  $e_d$ ,  $e_r$ ,  $T_r$ ,  $a$ ,  $b$ ,  $T_p$  when increased cause decrease in the output value.





**Fig. 7 Partial correlation coefficients (PCCs) for all input factors**

## DISCUSSION

The results described above correspond more or less to the expectations. Therefore, it supports the applicability of described combination of CFD and SimLab software. However, to be able to rely on the results and get some concrete recommendations either for manufacturers or for designers, more detailed studies have to be performed. For example from this study, it is obvious that there is no need for temperature of the floor to be a variable. For optimization, there is no need to assess its influence because it cannot be changed. Furthermore, to find out optimal distances between infrared heaters it would be better to replace both dimensions of the room with distances of surface  $S/2$  from each infrared heater separately in both directions  $x$  and  $y$ . Following previous description, you were not able to formulate any constructive conclusion. There is also a problem with the height of suspension. Obviously, the reciprocal proportion coming from figure 7 is not linear and that is why we need to take care a bit more of chosen range. In any case, there always occurs a question if the model behaves the same way all over the range of all input variables; there always occurs a question if the model is linear.

Results shown in this contribution confirm that sensitivity analysis can be a very useful source of information about behavior of any explicit or even implicit model. In case study, application to CFD model was described and concrete results were obtained. In order to get concrete recommendations a more detailed study has to be performed. Anyway, this example shows the way.

Recommendations for application of SA on CFD are as follows:

- 1) use rather less complicated models because of high computation cost and need of relatively large number of execution;
- 2) prefer Latin hypercube sampling rather than Random;
- 3) for optimization, eliminate the factors that you cannot change in reality, they would just distort results;

- 4) during all steps of the analysis, have in mind concrete goal you want to achieve.

## **ACKNOWLEDGEMENT**

The paper was supported by VZ MSM 684 077 0011. Special thanks belong to Ing.Peter Kotek from the Faculty of Civil Engineering, CTU in Prague, who was a coauthor of the study described in “input settings” paragraph.

## **REFERENCES**

- [1] ASHRAE: *ASHRAE Handbook of HVAC Systems and Equipment*. American Society of Heating, Refrigeration and Air Conditioning, Atlanta, 2000, ISBN 1-883413-81-8.
- [2] Saltelli, A., Chan, K. and Scott, E.M., *Sensitivity analysis*. 4 th ed. 2006. John Wiley & Sons Ltd. 475. 0-471-99892-3
- [3] Fluent 6.2 Software and Manual. Available at URL <<http://www.fluent.com/software/fluent/index.htm>>
- [4] Gambit 2.3 Software and Manual. Available at URL adrese <<http://www.fluent.com/software/gambit/index.htm>>
- [5] Simlab 2.2 Software and Reference manual. Available at URL <<http://simlab.jrc.cec.eu.int>>