Heat transfer in hybrid fibre reinforced concrete-steel composite column exposed to a gas-fired radiant heater

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Abstract. In the paper, a gas-fired radiant heater system for testing of structural elements and materials at elevated temperatures is described. The applicability of the system is illustrated on an example of the heat transfer experiment on a hybrid fibre reinforced concrete-steel composite column specimen. The results obtained during the test are closely analysed by common data visualization techniques. The experiment is simulated by a mathematical model of heat transfer, assuming the material data of the concrete determined by in-house measurements. The measured and calculated data are compared and discussed.

1. Introduction
High temperature experiments and fire tests have been widely utilized for the determination of material properties (mechanical, thermal or other physical properties) of heated materials as well as for studying the behaviour of heated structures or their parts (structural collapse, spalling of concrete, ignition and burning of timber elements etc.) [1–4].

An experimental investigation of structural behaviour in fire is usually performed in fire furnaces, mainly for separate structural members or parts of a structure, e.g. [1, 2], or, less commonly, by the full-scale fire tests of entire structures, e.g. [5]. However, these complex experiments are highly cost-consuming and hence, many researches have focused on the development of alternative types of experimental set-up which would be cheaper, easy to use, while maintaining the accuracy and validity [4]. For illustration, the works in which a heat source is formed by a direct flame gas burner, e.g. [6], by ceramic pads heaters, e.g. [7,8], or by radiant heaters – both electric or gas, e.g. [4,9,10], can be mentioned.

The ceramic pads heaters have been used at the Faculty of Civil Engineering (FCE), Czech technical university in Prague for many years, mainly for the investigation of high-temperature behaviour of steel structural members, e.g. [7], or for the determination of mechanical properties of heated concrete, e.g. [8].
Since 2014, a gas-fired radiant heater system has been developed at the FCE for helping to study the heat transfer in fibre reinforced concrete-steel composite members, within the scope of the research project GA15-19073S – Models of steel and fibre concrete composite columns exposed to fire.

The results obtained by this system are presented in this paper. These results were utilised for the design of a subsequent complex heat transfer experiment in a fire furnace, which was performed in PAVUS Fire Testing Laboratory at the end of 2016, see [11,12].

2. The gas-fired radiant heater system
The experimental set-up of the gas-fired radiant heater system, see figure 1, consists of: (i) a radiant heater, (ii) a gas cylinder with a hose and regulator, (iii) a steel stand, (iv) a datalogger connected to a computer, (v) a test specimen with thermocouples, cf. [4].

The radiant heater used in the presented system is a commercially available device made by a Czech manufacturing company. Namely, the KASPO K30-STL type has been used, with the following parameters from the user manual [13]: nominal heat output of 30 kW, burner gas pressure of 70–100 kPa (for propane/butane mixture), gas consumption of 2.3 kg per hour (for propane/butane mixture), and the dimensions as shown in figure 2. For the heater, it is possible to use a propane/butane mixture (as in this case) or natural gas.

Figure 1. Experimental set-up, cf. [4, Figs. 4, 5, 9].

Figure 2. Dimensions of the radiant heater (in mm): front view (left), side view (right), according to [13].
As mentioned above, the propane/butane mixture is used in the system. It is stored in 10 kg gas cylinders. This amount of gas serves for about 4 hours of continual heating. The gas regulator is set to a constant value of 100 kPa.

The steel stand is an in-house product made of steel L-profiles. It enables to adjust the position of the heater in vertical direction. The position of the heater remains constant during the test, cf. [4].

The datalogger is a custom-made device made by a Czech company. It contains 24 thermocouple ports (NST 1200 type) in total and one USB-B port for connecting to a computer. For recording the measured data in the computer, a custom-made software (provided by the datalogger producer) is used. The data are stored in a .dat file format. The datalogger is destined for use in connection with K type thermocouples – both normal and sheathed.

A test specimen can be made of any material. During the development and application of the heating system at the FCE, concrete, steel-concrete composite, steel as well as timber elements have been tested. One of these experiments is described below.

3. Experiment
In the following part of the paper, the heat transfer experiment on one test specimen of a composite circular column is presented. The specimen was heated by the gas-fired radiant heater described above.

3.1. Test specimen
The test specimen represents a hybrid fibre reinforced concrete-steel composite column. A steel tube of the length of 600 mm, outer diameter of 273 mm and the wall thickness of 6.3 mm was filled by hybrid (steel and polypropylene) fibre reinforced concrete. Its composition is given in table 1.

| Component                      | Content (kg/m³) |
|--------------------------------|-----------------|
| Cement CEM I 42.5 R            | 490             |
| Water                          | 158             |
| Aggregate 0/4 mm               | 890             |
| Aggregate 4/8 mm               | 100             |
| Aggregate 8/16 mm              | 745             |
| Plasticizer                    | 4.9             |
| Steel fibres Dramix 3D 80/60 BN| 40              |
| Polypropylene fibres Forta Ferro 54 mm | 3              |

During the concrete casting, thermocouples (TCs) and the steel support ensuring their position were inserted into the specimen, see figure 3. Nineteen K-type TCs (2 × φ 0.5 mm) in total were used for measuring the internal temperature (17 TCs within the test specimen) as well as the outer temperature near the surface (2 TCs on the steel shell). In the vertical direction, the thermocouples were placed in the middle of the specimen height. The positions of the thermocouples in the cross-section of the specimen are illustrated in figure 4. The specimen was cast in December 2015 (the set of 3 specimens was prepared, one of them was employed for the presented experiment), the heat transfer test was performed in May 2016.
3.2. Test procedure
The test specimen was placed right in front of the heater, see figure 1, in the position illustrated in figure 4. The system was assembled as described above. The outer thermocouples (TC18, TC19) were fixed to the steel shell using a steel wire. The contact between the surface thermocouples and the shell was not perfect – the distance between the TCs and the shell was about 2–4 mm, which will be discussed in the next part of the paper. The heating lasted for 3 hours, thereafter, the test was terminated. The gas regulator was set to a constant value of 100 kPa. At the end of the test, the gas pressure slightly decreased, see figure 5, due to the small amount of gas in the cylinder.

3.3. Results analysis
The data obtained during the experiment have the form of a .dat file containing the measured temperatures for each thermocouple in defined time steps (10 s in this case). The basic method for depicting the results is to draw a graph with a temperature-time curve for the given thermocouple. In this case, an in-house MATLAB [14] code is used for data conversion and visualization. The time evolution of the outer temperatures (TC18, TC19) is illustrated in figure 5. The temperature-time curves for the selected inner TCs (9, 10, 17, 2; see figure 4) are shown in figure 6.

In order to better illustrate the temperature distribution within the specimen during the test, the in-house MATLAB [14] code was written. Based on the linear interpolation in polar coordinates, the code enables to draw the temperature field for a given time of heating, cf. [15].

In figure 7, the measured temperatures for the selected times of heating (90 min, 180 min) are displayed in the appropriate positions within the cross-section. These data serve as input parameters for the interpolation. In figure 8, the resulting temperature fields for the time of heating of 90 min are depicted.

From the results described above and illustrated in figures 5–8, the following findings can be drawn.

- The gas-fired radiant heater system is able to generate relatively high temperatures in the test specimen – above 400 °C in 3 hours of heating; which makes it highly promising for this type of experiments.
The outer temperatures measured by TC18 and TC19 differ markedly – the difference reached about 100 °C. This is because the distances between these two thermocouples from the steel shell were not the same. It is obvious that it would be better to use a different type of thermocouples for measuring the boundary conditions in this case, e.g. sheathed thermocouples or plate thermometers instead of standard wire type thermocouples, see [15]. This is also discussed in the next part of the paper.

The direction of heating was not parallel to the horizontal axis of the specimen’s cross-section, as it was supposed, see figure 4. Firstly, it was believed that this was caused by the non-uniform air flow between the heater and the specimen due to wind – the experiment was performed outdoors. For that reason, a control experiment was done on the same specimen.
several months later – in December 2016, within a student project [15]. For this control experiment, lateral barriers were added to the heating system in order to avoid the air flow. However, the results obtained from the control experiment were almost the same as from the original one. Hence, the probable cause of the discrepancy between the supposed heating direction and the obtained results is a small rotation of the steel support with thermocouples during the casting of concrete. By performing a simple data analysis, based on the linear interpolation of the measured data, the angle of inclination of the heating direction was determined to be about 30° clockwise. This is taken into account in the modelling part.

4. Mathematical modelling
Mathematical modelling of heat transfer is applied in order to illustrate that the gas fired radiant heater experiment can be simulated by an appropriate model. It should be also verify that the model can be used for the hybrid fibre reinforced concrete, which is of particular interest for the subsequent complex heat transfer experiment in a fire furnace in PAVUS Fire Testing Laboratory in 2016 [12].

For the sake of simplicity, a common heat transfer mode is used, without any coupling with mass balance (the effect of moisture is neglected). A more comprehensive model will be employed in [12], see also [16,17] and references therein.

It is necessary to determine the boundary conditions, which can be used in the model and which would represent the character of heating during the test. Generally, the Dirichlet or the Neumann boundary conditions can be used [2,18]. For the first one, the temperature on the boundary is specified, for the second one, the heat flux on the boundary is assumed – as a function of temperature or as a prescribed function [2,18].

For the presented gas-fired radiant heater system, it seems to be suitable to determine the boundary conditions based on the heat flux generated by the heater, see [4]. This is however not possible in this case since this variable was not measured during the test.

The Dirichlet boundary condition cannot be used since the surface temperature was not monitored – the contact between the outer TCs (18, 19) with the steel shell was not perfect.
Hence, it seems to be suitable to determine the boundary condition based on the heat flux, convective and radiative, which is also in accordance with the standard fire design approach, see [19]. The heat flux can be calculated based on the gas temperature measured by the outer TCs (TC18 and/or TC19, see below).

It should be noted that in literature, more sophisticated methods to determine the boundary condition during experiment can be found. Let us mention the approach based on the adiabatic surface temperature, see e.g. [20–22], which, however, cannot be employed for the presented experiment since the plate thermometers were not used.

4.1. Model

The model with the unknown \( \theta(\mathbf{x}, t) \), where \( \mathbf{x} \in \Omega \), can be written in the form (taken from [2,18], see also [16,17]):

\[
\rho(\theta)c_p(\theta) \frac{\partial \theta}{\partial t} = \nabla \cdot (\lambda(\theta) \nabla \theta) \quad \text{in } \Omega, \tag{1}
\]

\[-(\lambda(\theta) \nabla \theta) \cdot \mathbf{n} = \alpha c(\theta - \theta_\infty) + \Phi \epsilon \sigma (\theta^4 - \theta_\infty^4) \quad \text{on } \Gamma_E, \tag{2}\]

\[\theta = \theta_0 \quad \text{in } \Omega, \tag{3}\]

where \( \Omega \) is the domain, \( \Gamma_E \) is the boundary exposed to the heat flux prescribed by equation (2), \( \theta \) [°C] is the temperature, \( \rho \) [kg m\(^{-3}\)], \( c_p \) [J kg\(^{-1}\) K\(^{-1}\)] and \( \lambda \) [W m\(^{-1}\) K\(^{-1}\)] are the density, the specific heat capacity, and the thermal conductivity of a material, respectively, \( \alpha \) [W m\(^{-2}\) K\(^{-1}\)] is the convective heat transfer coefficient, \( \Phi \) is the configuration factor, \( \epsilon \) [-] is the surface emissivity, \( \sigma \) [W m\(^{-2}\) K\(^{-4}\)] is the Stefan-Boltzmann constant, \( \theta_\infty \) [°C] is the ambient temperature, \( \theta_0 \) [°C] is the initial temperature, \( t \) [s] is the time of heating and \( T \) [s] is the total time of exposure [2,16–18].

4.2. Material properties

The material properties of the studied hybrid fibre reinforced concrete were determined by in-house measurements, see figures 9–11. The measurement procedures are described, e.g., in [23] and will be discussed in detail in [12].

![Figure 9. Density of the studied hybrid fibre reinforced concrete.](image1)

![Figure 10. Specific heat capacity of the studied hybrid fibre reinforced concrete.](image2)

For steel, the material properties (\( \rho \), \( c_p(\theta) \) and \( \lambda(\theta) \)) are assumed according to [24].
4.3. Boundary and initial conditions
The boundary conditions are assumed according to equation (2). By performing a set of calculations, it was observed that more appropriate results can be obtained when assuming the outer temperature as measured by TC19 (hence, TC18 is omitted hereafter).

Based on the direction of heating, the boundary of the specimen cross-section is divided in two parts, see figure 12. For these parts, the parameters of equation (2) are set, according to [19,24], as follows:

A: \( \theta_\infty(t) = \theta_{TC19}(t), \alpha_c = 25 \text{ W m}^{-2} \text{K}^{-1}, \epsilon = 0.7, \Phi(x) \in (0,1) \) (see figure 12);
B: \( \theta_\infty = 25 ^\circ\text{C} \) (approximate air temperature during the test), \( \alpha_c = 9 \text{ W m}^{-2} \text{K}^{-1}, \epsilon = 0; \)

where \( \theta_{TC19}(t) \) is the time evolution of the outer temperature measured by TC19.

For the initial condition, see equation (3), the uniform distribution of temperature across the section is assumed, with \( \theta_0 = 23.4 ^\circ\text{C} \), which is the mean value (with the standard deviation of 0.67 \( ^\circ\text{C} \)) of the inner TCs (TC1–TC17) temperatures measured before the start of the test.

4.4. Numerical simulation
System described by equations (1)–(3) was solved by the finite element method, implemented into the in-house MATLAB [14] code. For the spatial discretization, 3244 linear isoparametric triangular elements were used. Discretization in time was performed by the semi-implicit difference scheme, with the time step of 20 s [16,17].

4.5. Results and discussion
In figures 13–14, the results obtained from the numerical simulation are compared with the data measured during the test. It is obvious that the gas fired radiant heater experiment can be simulated by an appropriate model, while achieving high levels of accuracy. The model, despite its simplicity, works quite well also for the hybrid fibre concrete used in this case. The small discrepancy between the measured and calculated results is probably caused by (i) neglecting the effect of moisture transfer and phase changes and employing a simple heat transfer model, (ii) assuming a simplified approach to determine the boundary conditions used in the model. The first point will be discussed in detail in [12]. The second one will be fixed in the next experiment by using the plate thermometers or the heat flux gauge, cf. [4].
Figure 13. Comparison of temperature fields.

Figure 14. Comparison of temperatures for the thermocouples on the top-left to bottom-right diagonal (left) and on the bottom-left to top-right diagonal (right), see figure 4.
5. Conclusions
In the paper, the newly designed gas-fired radiant heater system for testing of structural elements and materials at elevated temperatures was described. The system has been developed at the CTU in Prague since 2014. The applicability of the system was illustrated on an example of the heat transfer experiment on the hybrid fibre reinforced concrete-steel composite column specimen. It was demonstrated that: (i) the gas fired radiant heater system is able to generate relatively high temperatures in the test specimen, which makes it highly promising for this type of experiments; (ii) the crucial aspect for modelling of such experiment is to determine the boundary conditions properly (e.g. based on the plate thermometers measurement); (iii) the gas fired radiant heater experiment can be simulated by an appropriate model, while achieving high levels of accuracy; (iv) the model works quite well also for the hybrid fibre concrete – if its material properties are known.

The results obtained by the system were utilised for the design of a subsequent complex heat transfer experiment performed in PAVUS Fire Testing Lab. furnace at the end of 2016 [11,12].

The next step in the development of the system will be focused on the improvement of boundary conditions measurements and simulation.

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