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Analysis of external temperature profiles in tubes with inserted turbulators using thermography

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Abstract

Enhancement of heat transfer intensity in all types of thermo technical apparatus is of great significance for industry. Beside the savings of primary energy, it also leads to a reduction in size and weight. Up to the present, several heat transfer enhancement techniques have been developed. One of them is using turbulators. In this technique, because of a large number of parameters involved, and rather complex fluid flow structure, usually a complex measurement set is needed to characterize a tested model. This situation could be simplified using thermography, which is expected to bring about simpler and faster measurements, ending up with sufficient measurement data.

This paper deals with external temperature profiles on a smooth tube and on tubes inserted with turbulators, recorded thermographycally. In order to access the induced heat transfer enhancement, an experimental set-up was designed which includes a ventilator, a mass flow measuring orifice, an air-heater and the investigated tube cooled in still air. In the measurements, the effects of three types of turbulators on the external temperature profile of the tube were analyzed. Inside the investigated tube (∅48.3x2.9 mm, length 1000 mm) air is used as the heat transfer medium. Using recorded thermograms, the differences in heat transfer were determined.

1. Introduction

The need to save energy and to reduce dimensions and costs of apparatus has stimulated the search for various techniques of enhancing heat transfer. Most of this enhancement techniques are reviewed in references [1] and [2]. In the present study tube inserts (also called turbulence promoters or turbulators) for forced flow, creating rotating and/or secondary flow are analyzed. As early as 1921 Royds first observed the beneficial effect of turbulators on heat transfer. Since then, many different types of turbulators have been evaluated and examined by various investigators in order to enhance the heat transfer, such as all kind of tape inserts (continuous twisted tape, segmented twisted tape, kinex mixer, helical tape, bent strips), extended surface inserts, helical coil inserts, mesh or brush inserts and displaced inserts.

Nowadays, internal fins and integral roughness, as two newly developed approaches to enhancement of tube side convective heat transfer, are becoming more important. However, turbulator inserts, as the earliest approach to the tube-side enhancement, are still convenient and also the cheapest way to upgrade the efficiency of an already existing apparatus. The object of the present investigation, motivated by a manufacturer of fire-tube boilers, is to explore and compare the effect of three different types of turbulators on the heat transfer process by determination of the external temperature profile on tubes with inserted turbulators using thermography.

2. Experimental apparatus and procedure

The measurements are performed in an experimental setup involving a single steel tube, supplied with hot air via a ventilator and electric heater. The outside of the tube is cooled in still ambient air - Figure 1. The airflow rate may be variated by throttling the ventilator inlet and the inlet hot air temperature by control of the electric heater current.

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The following quantities are measured:

- mass flow rate of air according to DIN 1952
- hot air inlet end exit temperature
- test tube outside wall temperature distribution by means of thermography (IR camera AGEMA 570 PRO) and one spot measurement by means of a thermocouple in the middle of the test tube.

Three types of turbulators were inserted to the test tube during the experiments: helical coil (type B), twisted tape (type C) and perforated tape (type D). The inserts are shown in Figure 2. They are fitting tightly to the inside wall of the tube. Their dimensions are listed in Table 1. Tests with the smooth tube (tube without insert, type A) were also performed.

Table 1: *Turbulator characteristics for test tube of 42.5 mm inside diameter*

	Smooth	Turbulators		
Geometry	tube Type **A**	Helical coil Type **B**	Twisted tape Type **C**	Tape Type **D**
Overall length L, mm	1000	1000	975	600
Pitch s, mm	–	24	300	80
Tape thickness t /wire diameter d_{wire}, mm	–	4	2	0.5

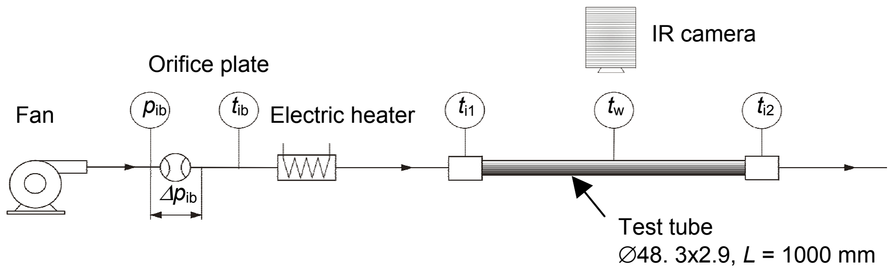

Fig. 1. *Schematic of experimental setup*

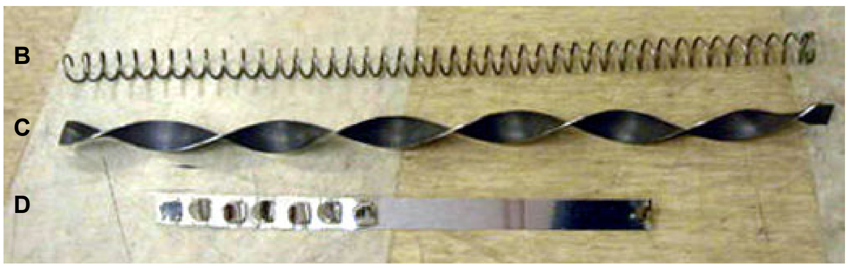

Fig. 2. *Turbulators tested in present work*

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3. Literature survey

3.1 Helical coil inserts

Helical coil inserts may also be considered as “wall-attached roughness”. Their enhancement mechanism is the same as the one of helical-rib roughness.

Correlations developed in studies concerning the problem of the heat transfer and pressure drop in helical-coil-inserted tubes are often valid only within a limited range of flow conditions.

Up to now only the influences of the pitch *s* and the wire size d_{wire} have been reported. The influence of the length of the helical coil and its position in tube was considered in a study of Ponweiser and Malinovec [3]. The influence of the pitch was also tested. Developed correlations for heat transfer and friction factor are valid for the wire diameter d_{wire}=3 mm only. The influence of the position of the helical coil insert in the tube on the heat transfer rate was found negligible, but on the friction factor it was significant.

Zhang, Li and Liang [4] investigated the heat transfer and friction of hot air, regarding the influence of pitch *s* and wire diameter d_{wire} of the helical coils in tubes. The length of the test tube section was 1000 mm and its inner tube diameter was 56.32 mm. The air was heated to 200±5°C. The resulting correlation is

$$Nu = 0.253\,\mathrm{Re}^{0.716}\left(\frac{d_{wire}}{d_i}\right)^{0.372}\left(\frac{s}{d_i}\right)^{-0.171} \quad (1)$$

and is valid for: $6000 \le Re \le 100000$, $0.037 \le d_{wire}/d_i \le 0.10$, $0.35 \le s/d_i \le 2.50$

The correlation may be used only when the insert covers the whole length of the tube.

Kumar and Judd [5] examined the influence of helical coils inserted in a vertical tube on the heat transfer and the pressure drop. Water was used as the test fluid. The pitch (s/d_i=1÷5.5) and the wire size d_{wire} (1.3, 1,6 and 1.83 mm) were varied. The inlet temperature of the water was between 26 and 33°C. The maximum increase of heat transfer reaching 280% was achieved. At the same time a large increase of pressure drop was determined.

They developed the following relation:

$$\frac{Nu}{Pr^{1/3}} = 0.0554\left(C_f Re^3\right)^{0.286} \quad (2)$$

where C_f is the Fannig friction factor.

This equation was found to be independent of the tube diameter d_i, the wire diameter d_{wire}, the pitch *s* and the test fluid. The usage of the formula is limited by problems in determining the Fannig factor.

Uttarwar and Raja Rao [6] examined the influence of seven different helical coils on the heat transfer and the pressure drop in laminar flow using high viscous Servotherm oil. As the Prandtl number and the Reynolds number as well as the inside diameter of the pipe in this work lie outside of the indicated ranges of validity the formula is not usable in the present case either.

Klaczak [7] made investigations with a helical coils using water as the test fluid. The developed heat transfer correlation is not valid for air. Measurements were performed in two Reynolds number ranges, $800 \le Re \le 8000$ and $5000 \le Re \le 20000$.

Measurements by Sethumadhavan and Raja Rao [8] were performed with eight helical coils with two different wire sizes (2 and 3 mm) and with four different pitches (10, 22, 38 and 66 mm). Heat transfer and friction factor correlations were developed. In both correlations the Nusselt number and friction factor cannot be expressed explicitly.

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3.2 Twisted tape inserts

Twisted tape inserts cause the flow to spiral along the tube. Their potential performance is diminished because the thermal contact of the tape and the tube wall is not ideal, so they do not perform as well as "wall-attached roughness". They enhance the heat transfer due to the increased tangential velocity component and reduced flow cross section.

Many author have investigated the twisted tape inserts. Manglik and Bergles (see Ref. [1]) developed the most recent heat transfer correlation, based on the asymptotic method and valid for T_w=constant and q=constant with Re > 10000.It is given by:

$$Nu = \left(1 + \frac{0.769}{y}\right) Nu_{y=\infty} \tag{3}$$

where:

$$y = \frac{s}{2d_i} \tag{4}$$

and $Nu_{y=\infty}$ for straight tape:

$$Nu_{y=\infty} = 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \left(\frac{\pi}{\pi - 4t/d_i}\right)^{0.8} \left(\frac{\pi + 2 - 2t/d_i}{\pi - 4t/d_i}\right)^{0.2} \left(\frac{T_i}{T_W}\right)^{0.15} \tag{5}$$

The authors also propose a friction factor correlation.

4. Results and discussion

The experimental results presented in this paper are preliminary ones, performed in order to ascertain the possibility of recording surface temperatures, which will disclose various turbulators, inserted in tubes charged with hot gases. The tests have been carried out for a constant Reynolds number $Re \cong 38000$, based on the inner tube diameter d_i = 42.5 mm and the hot air velocity calculated from the mass flow $\dot{m}_i$. The inlet temperature of air is kept constant during all measurements ($t_{i1} \cong 175°C$).

Recorded IR images of the four different tube geometries type A, type B, type C and type D are shown in Figure 3. Each tested tube geometry produces a different wall temperature distribution as shown in Figure 4 representing the temperature profile along the line indicated at each tube thermogram in Fig.3. It is well known that the heat transfer enhancement performed by different types of turbulators depends on their geometry. Hence, the better the efficiency of the turbulator, the closer the external wall temperature to the temperature of the hot air flowing through the tube in the present experiments. This justifies the results shown in Fig. 4 where the mean wall temperatures of tubes with inserted turbulators (type B, type C and type D) are higher than in the case of the smooth tube without turbulator (type A).

However, the thermograms and the recorded temperature profiles reveal even more details about the nature and geometry of the inserts. The helical coil turbulator (type B) appears to be most efficient among the three tested models, because it yields the highest outside mean wall temperature of the tube. As shown in Figure 2 the tested twisted tape turbulator (type C) has six twists, resulting in clearly visible effects in the wall temperature distribution curve showing local maxima and minima. Only in the tube entrance region the effect of the first twist is not clearly recorded. The type D turbulator also yielded very interesting results. As requested by the boiler manufacturer its overall length was 600 mm, and the turbulator was placed in the middle of the tested tube. Therefore its perforations and deflectors become effective only in the rear half of the tube. In the first half of the tube, the temperature profile is therefore similar to the smooth tube. This is abruptly

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interrupted in the turbulator region where a steep rise of the wall temperature is recorded. It is supposed that this is the result of two effects: the mixing of the hot central stream with the periphery and the heat transfer intensification due to increased turbulence.

5. Conclusion

In the present work thermography was used for investigations of the effectiveness of various types of turbulators suitable for the heat transfer augmentation in fire tube boilers.

According to the obtained experimental results it may be concluded that changes of the inside heat transfer coefficient can be recorded with IR thermography by measuring the external wall temperature distribution at the tube.

In order to quantify the improved heat transfer due to turbulators, the future investigations will be performed using a similar model, but with intensive heat transfer at the outside tube wall. This will allow accurate heat balancing of the heat transfer.

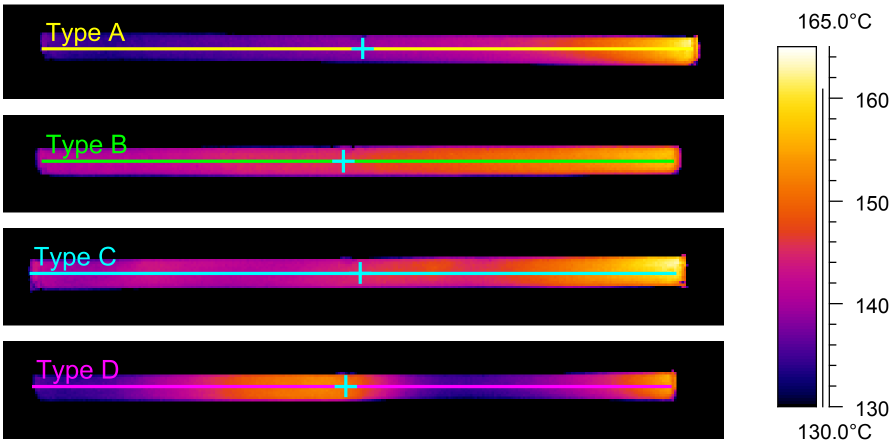

Fig. 3. *IR images of the four tested tubes*

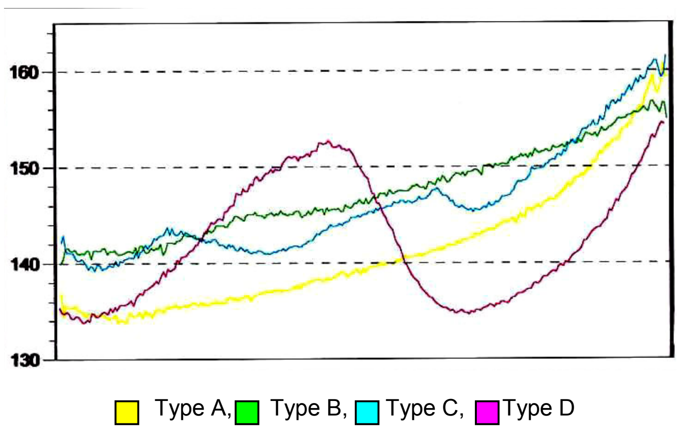

Fig. 4. *Temperature profiles at tube centerlines indicated in Fig. 3*

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