TEMPERATURE MEASUREMENT IN AIR DUCTS
- AN OPTIMIZED METHOD FOR SOLAR AIR HEATERS

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Synopsis

Facing the fact that a growing number of companies are pushing the market for solar air heaters Fraunhofer ISE is developing and improving well defined and precise measuring methods to characterize such solar air heaters. This work is done within the project Luko-E[1] with the aim to standardize tests not only regarding performance measurements but also regarding reliability testing.

The thermal efficiency of the solar air heater depends mainly on the factors mass flow, irradiance, and temperature lift. One key element of high quality test results is an accurate measuring method of the temperature which are quite quite complicated to achieve within airstreams because of many influencing variables.

In this paper the problematic of temperature measurements in air channels is discussed and two different air temperature measurement methods are compared.

In the first method, the air temperature layers in the channel are mixed by an air blender, generating a uniform temperature profile according to the recommendations of ANSI ASHRAE 93.

The second method determines the temperature using a net to homogenize the airstreams velocity in front of a temperature sensor which measures a mean value by integrating the temperature over its sensors length.

1. Theoretical background for air temperature measurement

The temperature of the air in a channel depends on different variables; therefore a comprehensive analysis using computational fluid dynamics is needed to simulate the behavior. The equations describing the situation are the continuity equation (1), the moment equation (2) and the energy equation (3). These equations in differential form are:

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[1] LuKo-E is supported by the German Federal Ministry for Environment BMU and PTJ

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \qquad (1)$$

$$\rho \frac{dv}{dt} = \rho g - \nabla p + \nabla \cdot \tau_{ij} \qquad (2)$$

$$\rho \frac{de}{dt} + v \cdot \nabla p = \nabla \cdot (k \nabla T) + \nabla \cdot (v \cdot \tau_{ij}) \qquad (3)$$

ρ - density
t – time
v – velocity
g – gravity of earth
p – pressure
τ – friction term
k – thermal conductivity
e – specific energy
u – specific internal energy
T - Temperature
c – specific heat
A - area

According to these equations there are five variables (ρ, V, p, u and T) but only three equations are provided. The other two equations needed are provided by the equations for state of a gas.

$$\begin{aligned} \rho &= \rho(p,T) \\ u &= u(p,T) \end{aligned} \qquad (4 \text{ and } 5)$$

Theoretical solutions for these problems can only be provided considering many assumptions such as that the fluid to be modeled is behaving as a Newtonian fluid. The fluid to be modeled is assumed to be incompressible or assumed to be an ideal gas. Computational fluid dynamic programs are often applied to solve more complicated (and closer to the reality) situations.

The calculation of the temperature in air channels involves a lot of variants and must be analyzed carefully. One example is that due to the air density gradient, induced by temperature differences and changes in the floating directions, flowing air in a circular pipe cannot be considered to be axial symmetric.

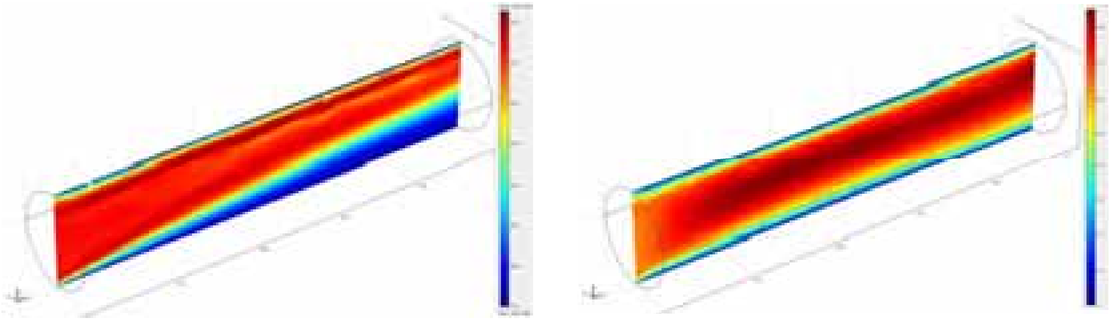


Figure 1 and 2: Results of fluid dynamic analysis of the temperature distribution (left) and the air velocity distribution (right) of an air duct of one meter length. The flow direction is from left to right. The minimum values (blue) are 0°C (273 K) and 0m/s; maximum values (red) are 67°C (340 K) and 0.85 m/s.

In order to describe the temperature of constructions like solar air heaters which are assembled from different parts and materials it is reasonable to define a thermal mean temperature; in this case this mean temperature is defined as the sum of all single parts weight with their respective heat capacity and temperature in relation to the sum of their thermal capacity and mass.

$$T_{m,th} = \frac{\sum_{i=1}^{n} m_i c_i T_i}{\sum_{i=1}^{n} m_i c_i} \qquad (6)$$

This equation has to be transformed to describe the real mean temperature in the air channel. Therefore an integral over the entire normal surface area needs to be determined considering all the depending variables. With this transformation the thermal mean temperature is now called mixed-temperature.

$$T_{m,th} = \frac{\int_A T(A)v(A)\rho(A)c(A)dA}{\int_A v(A)\rho(A)c(A)dA} \qquad (7)$$

Deriving from this equation one can see what parameters have to be measured at each point of the cross section area to give a mean temperature of the testing fluid. These are:

- local temperature
- local density
- local heat capacity (depending on humidity)
- local air velocity

Equation (8) shows that the temperature is beneath others depending on the fluid velocity. This means that the temperature measurement has to consider the velocity profile in order to give a valuable result. To simplify the process one can consider the density and the specific heat as constant within one cross section area along the channel [1].

The reduced expression for the mixed temperature is then as follows:

$$T_{m,th} = \frac{1}{Av_m} \int_A T(A)v(A)dA \qquad (8)$$

2. Comparison of two methods for temperature measurement in gas streams

In the following chapters two methods for temperature measurements are described, their advantages and disadvantages are discussed, and finally a suggestion is made how the measurement can be standardized. The aim is to identify a suitable method to measure the reference temperatures for a caloric characterization of solar air heaters.

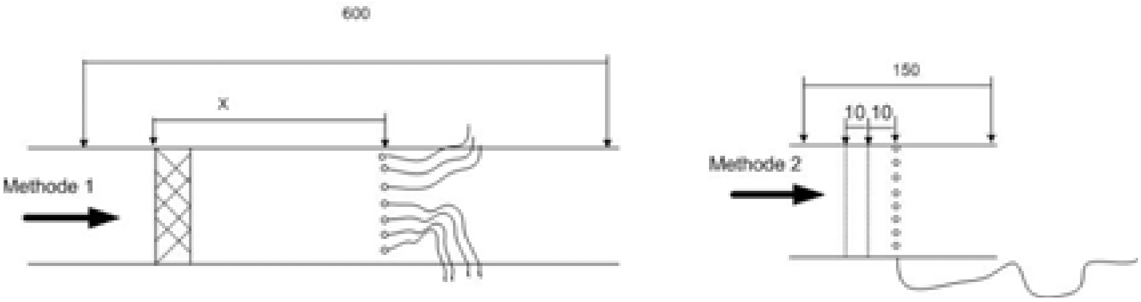


Figure 3: Sketch of method 1 using a blender and multi-sensor temperature measurement unit (left) and method 2 using two net and an integrating temperature sensor (right)

2.1 Method 1 – multi-temperature sensors with air blender

In this method the gas is mixed with an air blender (figure 3 left) to ensure a preferably homogenous temperature profile. This profile is homogenous but only at a certain distance behind the blender depending on the Reynolds number of the flow situation.

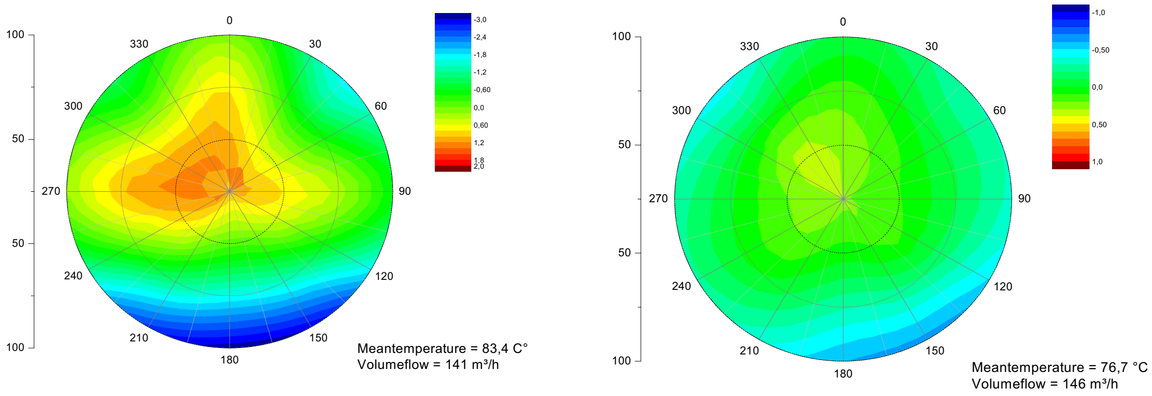


Figure 4 (left) and 5 (right): Temperature distribution measured in a 200 mm air duct. The left figure shows the temperature distribution without blender. The mean temperature is 83.4 °C, the temperatur variation is 3.3 K; the volumetric flow is 141 m³/h. The right figure shows the mixed air temperature by using an air blender measured 34 cm behind the air blender. The mean temperature is 76.7 °C, the temperature variation is 0.7 K; the volumetric flow is 146 m³/h.

By using an air blender the homogeneity of the temperature distribution across the surface at a special distance after the blender can reach values up to +/- 0.35 K. In case of not using an air blender the temperature differences exceeds in this case 3.3 K. The distance between blender and temperature measurement is influencing the homogeneity as well as the velocity of the air stream. These influences are shown in figure 6.

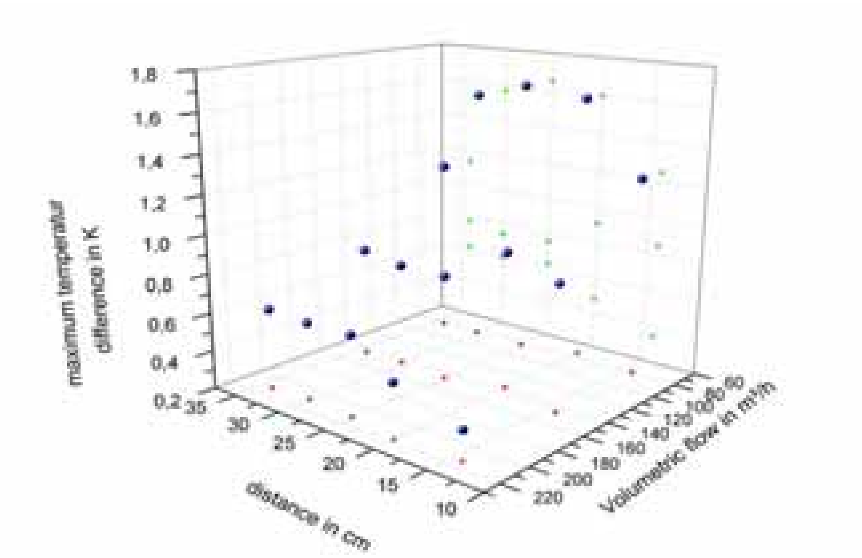


Figure 6: Maximum temperature differences within a cross section caused by the distance between blender and temperature sensor unit and by the velocity (volumetric flow) of the stream. The green and red points are the projected measured points in xy-plane and yz-plane.

The distance between temperature sensor and air blender was varied from 140 to 350 mm for these experiments. The complete length of the temperature measuring device with air blender reaches up to 600 mm and more. This can cause influences on the temperature because the whole channel length has to be insulated properly.

Table 1: Advantages and disadvantages of method 1

Advantages	Disadvantages
Repeatable and well suitable temperature profile achieved by installing a blender	Dependence of the distance between air blender and temperature sensor on the Reynolds number. The temperature sensor has to be moved depending on the velocity. In normal operation the sensors are fixed at on position with the result of higher inhomogeneity.
The blender only generates low pressure losses in the measurement channels	The measurement error depends on the homogeneity of the temperature distribution
	Large surface area of the air channels leads to thermal losses because the channel length is determined by dependencies described above
	Thermal losses must be considered by the thermal performance of the solar air heater. Due to the high number of sensors needed it is not possible to calibrate the thermal losses of the sensors
	Many sensors are needed in order to supervise a good homogeneity

2.2 Method 2 – integrating temperature sensor with two nets

In method 2 the sensor unit consists of two nets along the channel within a distance of 10 mm in order to provide a uniform velocity profile (see figure 3, right). The temperature is measured behind these nets with a spiral sensor covering homogeneously the channel area [3]. The distance between the net and the spiral sensor is 10 mm.

The length of the equidistant temperature sensor depends on the diameter of the air duct and the radian distance between each winding of the sensor. The geometry of the nets has to be analyzed in case studies, it depends on the volumetric flow and the diameter of the air duct.

Table 2: Advantages and disadvantages of method 2

Advantages	Disadvantages
Velocity profile can be considered uniform	Need to analyze the effect of the net on air flow. An optimized net is required for this measuring method.
Only one signal sensor	pressure drop caused by the sensor
Smaller space needed leading to a smaller surface area. The distance between temperature sensor and solar air heater can be reduced to 100 mm. The total construction length can be reduced to 150 mm	

Preconditions for using method 2 are a homogenous velocity distribution and that the nets have no influence on the temperature measurement. Four case studies representing different standard situations present the function of a properly working temperature sensor. The purpose to make these three different cases is to provide different flow conditions and study the effect on the temperature profile and consequently the effect on the temperature measurement. These situations are assumed to occur when characterizing different air heater products.

The first configuration consists of a 3 m straight pipe where the sensor is placed at the end of the pipe.

In the second configuration the sensor is placed behind a 90º bow. In front of the bow a 3 m pipe is placed in order to avoid disturbance on the fluid profile.

The third case study is a diffuser causing a diameter change from 120 mm to 200 mm.

Effect of the net on flow speed

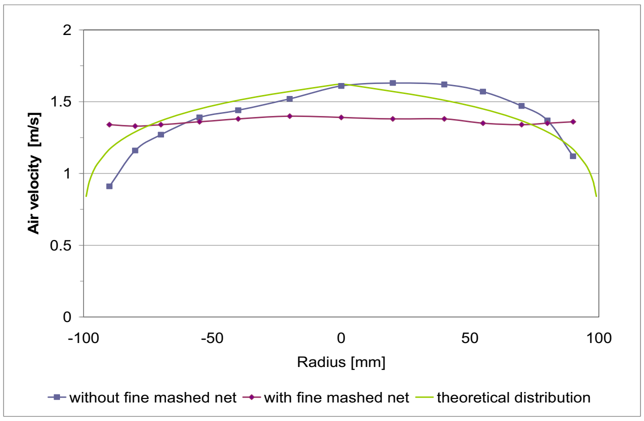
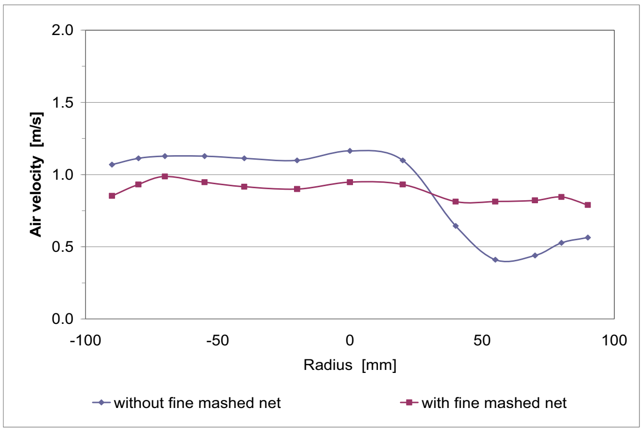


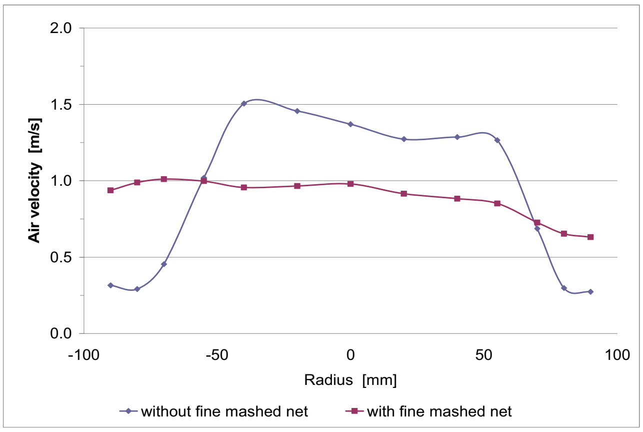
Figure 8: Distribution of the air velocity in a straight air duct

In figure 8 the distribution of the air velocity in a horizontal line through a straight air duct is shown (flow direction from bottom to top). The blue graph shows the measurement values without fine meshed nets. The violet line shows the straightened profile after the fine meshed nets. The green line demonstrates the theoretical line calculated according to NICURADSE []. The calculated variance is reduced by using the fine meshed net enormously (from $5 \cdot 10^{-2}$ to $5 \cdot 10^{-5}$).



The blue line in figure 9 shows the velocity profile after a 90° bow. The inner circular part of the bow (positive radial values) shows a reduced velocity. The outer circular part of the bow shows a higher velocity. Both effects are compensated by the net. Variance is reduced from $9{\cdot}10^{-2}$ to $4{\cdot}10^{-3}$ by using the nets.

Figure 9: Distribution of the air velocity after a 90° bow



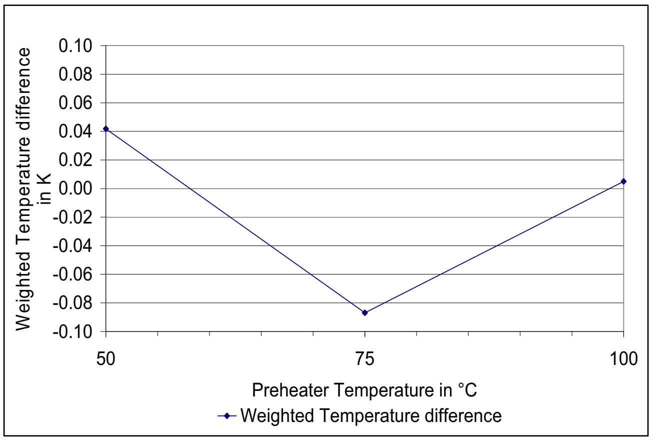
The air ducts in solar air heaters often vary in the geometry and it is necessary to use diffusers in order to adapt it to the measurement devices. In this case the distribution of air velocity is extremely disturbed. In figure 10 this distribution is represented by the blue line. The effect of diameter change from 120 to 200 mm is reflected in the flow distribution. The fine meshed net reduced the inhomogeneous profile. The calculated variance is reduced from 0.253 to 0.017 by using the fine meshed nets.

Figure 10: Distribution of the air velocity after a diffuser 120/200 mm

It can be observed that the net provides a uniform velocity profile. Therefore the temperature measured by the spiral sensor is accurate since there is not need to weight the temperatures across the cross section.

Effect of the net on the temperature

To analyze the influence of the net on the temperature following experiment was performed. The air stream was heated, after temperature and volumetric flow were measured with and without net. In order to estimate the possible effects, such as heat transfer or radiation exchange from the net to the channel surface or to the sensor surface, of the net on the temperature in stationary conditions, the volumetric flow was kept constant. The temperature was measured in a horizontal axis with 6 points which cover the same circular area. The temperature was weighted by the velocity. The graphic below shows the difference of this weighted temperature and the temperature of the air heater.



These results show that the net has no significant effect on the measured temperature and its influence can be neglected in a stationary measurement.

Figure 9: Weighted temperature difference at different preheated temperature levels (50, 75 and 100 °C)

3. Conclusion

Both measuring methods of temperatures in air channels are leading to accurate results if they are executed in a proper way. Both types of sensor units have advantages and disadvantages. In the case of using the temperature sensor with an air blender (method 1) many single point sensors are needed. The minimum number of sensors should be 12 for a 200 mm air duct per temperature measurement point. This leads to a relative high uncertainty by the calibration of the sensor units. Because of the fact that the homogeneity of the temperature depends on the temperature level, geometry of the air duct and also on the flow parameters, the measured arithmetic mean temperature differs from the real mean weighted temperature (equation 7). To reduce the error of measurements different temperature layers have to be mixed to get an acceptable mean value. The ANSI ASHRAE 93 -2003 requires a value with a tolerance of +/- 0.5 K [2]. To reach this value a properly working air blender is necessary. The temperature profile uniformity depends when using a mixing device from the Reynolds number of the flow and the distance between the air blender and temperature sensors. To characterize a solar air heater it has to be measured with several volume flows thereby the temperature homogeneity can vary. The advantage of this sensor unit type is the possibility of temperature profile visualization. On the other side the complete construction length can reach values up to 600 mm and more. The heat losses over the similar distance before and after the solar air heater have to be considered by calculation of the solar air heater performance. Therefore this method is very sensitive to varying products and boundary conditions and seems to be critical to handle.

In the case of using the temperature sensor with nets (method 2), only one sensor is needed. The sensor is placed representing uniformly the normal area of the air duct. This can be realized by applying the sensor in an Archimedean spiral. To be able to use equation 8 and ensure that the measured temperature is the mean weighted temperature the air velocity has to be uniformed. This can be realized by placing two fine meshed nets in short distances in front of the temperature sensor. The fine meshed net guarantees that the distribution of the air velocity is homogenous even after the air passed a 90° bow or a diffuser. With case studies optimized net geometry can be found. The construction length of this kind of sensor can be reduced up to 1/4 of the length in comparison to the length of the sensor unit using an air blender. The sensor measures the temperature directly at the solar air heater inlet and outlet. Due to this fact the influence of the surrounding environment is reduced (the influence of heat losses, wind speed and irradiation). The heat loss between inlet and outlet sensor can be calibrated in such a way that no recalculation is necessary.

Therefore we suggest the application of method 2 with a spiral temperature sensor and a net as the standardized method for temperature measurements in air ducts for the characterization of solar air heaters.

4. References

[1] F. Brenhard (2004): *Technische Temperaturmessung* , Springer Verlag

[2] ANSI ASHRAE 93 - 2003: *Methods of Testing to Determine the Thermal Performance of Solar Collectors*

[3] R. Digel: *Messung der mittleren Temperatur strömender Luft in Kanälen unterschiedlichen Querschnitt. Stuttgart*, direkte Korrespondenz