Měření rychlosti a modelování proudění vzduchu pro účely ochlazování válcovaného materiálu

Velocity measurement and modelling of airflow for the purpose of cooling the rolled material

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In metallurgy, measurement of fluids flow rate and velocity, e.g. cooling water, air or heating gases, is usually a key part of the process control system with significant influence on quality and economy of the process. Controlled cooling of steel wire requires a specific amount and distribution of air over the width and length of the cooling conveyor. For purposes of measurement during adjusting of the technology, the originally recommended vane anemometer was compared to measurement based on pressure difference by Pitot and Prandtl tubes. Differences in the results obtained by these three types of sensors as well as sensitivity to the probe distance from the nozzle outlet and deviation of the sensor longitudinal axis from the flow direction were evaluated in the laboratory. CFD calculations of the air velocity profile in the nozzle outlet were done and compared to the measured values.

Key words: *fluid flow; measurement; CFD simulation*

V metalurgickém průmyslu je měření průtoků a rychlosti tekutin jako chladicí vody, vzduchu nebo topných plynů obvykle klíčovou součástí systému regulace provozu s významným vlivem na kvalitu a ekonomiku procesu. Proces řízeného ochlazování válcovaného drátu vyžaduje určité množství a rozdělení vzduchu po šířce a délce chladicího dopravníku. Pro účely měření během seřizování technologie byl (původně doporučený) vrtulkový anemometr porovnán s měřením na základě diferenčního tlaku za použití Pitotovy a Prandtlovy trubice. Rozdíly naměřených hodnot pomocí všech tří sond a také citlivost na vzdálenost snímače od ústí dýzy a úhlovou odchylku podélné osy snímače od směru proudění byly laboratorně vyhodnoceny. Pitotova trubice vykázala téměř stejné naměřené hodnoty jako Prandtlova trubice. Pitotova trubice vykázala menší odchylku měřené rychlosti způsobenou odklonem osy snímače vůči směru proudu v porovnání s Prandtlovou trubicí. Z celkového porovnání užitných vlastností, odolnosti, investiční náročnosti a přesnosti měření vychází užití Pitotovy trubice v náročných podmínkách válcoven jako nejvýhodnější ze všech tří porovnávaných sond. Získané výsledky měření na laboratorní dýze byly porovnány s CFD simulací. Pro simulaci byly použity výpočetní modely k-ε-realizable, RNG, Spallart-Allmaras, k-ω-realizable, Reynolds-Stress SST a DES. Ve srovnání s naměřenými hodnotami vykázal model k-ε-realizable nejmenší rychlostní odchylku v ose proudu 1,24 $m \cdot s^{-1}$,což je rozdíl 4,4 % oproti naměřené hodnotě po celé šířce proudu z modelu dýzy.

Klíčová slova: *proudění tekutin; měření; CFD modelování*

1. Introduction

Heat removal from hot metallurgical products can be conducted in several ways which are based on convective heat transfer from the product into a cooling medium and heat transfer by radiation. Commonly used cooling mediums are water, oil and air. The air can be in some cases a suitable option as it does not pollute the surrounding space by vapor and liquid. The cooling effect is more controllable over a wide range, starting at very low values. There is also no issue that would cause a non-linear cooling effect as a Leidenfrost effect. Air is therefore used for cooling rolled railway rails, wires etc.

Increasing quality demands of hot rolled products require precise control of the whole manufacturing process from steel production, continuous casting through rolling to the final cooling operation. Excessive cooling rate shifts material structure more into the quenched one. Decreased cooling rate shifts material structure close to the annealed one. Proper adjustment of the cooling intensity is important for the transformation of austenite to the desired structures [1, 2].

In case of hot wire rolling, the material should be cooled equally around the perimeter of the loops lying on the cooling conveyor to obtain mechanical properties within a desired narrow range. The wire can be cooled either with a decreased rate under a cover with limited radiation to the surroundings, normally by natural convection and radiation or with increased rate by the air stream from fans located beneath the conveyor. As wire loops are partially laid across each other on the conveyor, more air should be directed to zones with more layers of wire.

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Air flow rate and velocity are set to meet technological parameters. Compliance with desired values should be controlled by measurement. A common method of such measurement involves a manual procedure using a micro vane flow meter (anemometer). Such a method is laborious, increases the risk of sensor destruction by solid particles in the flowing air and provides low accuracy and repeatability due to uneven and unsteady airflow. The paper deals with a measurement technique that provides an easier, safer and robust measurement while using a different type of sensor.

2. Goals and methods

Fluid volume or mass flow can be measured by numerous devices based on different physical principles. Some register force from flowing medium impacting measuring device (vane air flow meters), some evaluate the cooling effect of fluid flow (hot wire, hot rod method), other register differential or total pressure in fluid [3]. The latter method is suitable for metallurgical plants for its robustness, simplicity and durability.

From Bernoulli´s equation which presents the law of energy conservation, it is possible to derive velocity from the sensed difference between the total and static pressure. However, for very low Reynolds numbers, computations are more accurate using Stokes' Law [4]. Normalization to standard conditions can be calculated by temperature and humidity compensation. These types of sensors can also be used for measuring very low liquid flow velocities [5] as well as very high velocities, e.g. in avionics.

The manufactured rolled wire is cooled by air coming from nozzles located between rollers. The amount and distribution of air in the direction perpendicular to the wire is crucial for the cooling process, see Fig. 1.

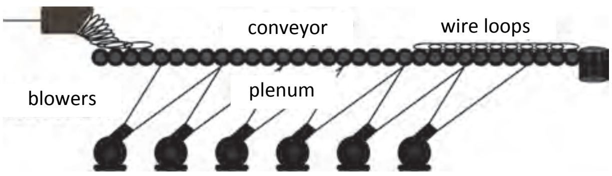

Fig. 1 Diagram of cooling conveyor [6]
Obr. 1 Schéma chladicího dopravníku [6]

According to the production facility manufacturer, a vane anemometer was recommended for the air distribution adjustment, but due to difficult work conditions and excessive time demand, evaluating air velocity from the measured differential pressure was used during an experiment [7]. In particular, Pitot and Prandtl tubes were considered. The concern was, whether those methods deliver the same results. The Pitot tube was compared to Prandtl tube, and vane anemometer during velocity measurements near the rectangular outlet of the laboratory nozzle, see Fig. 2.

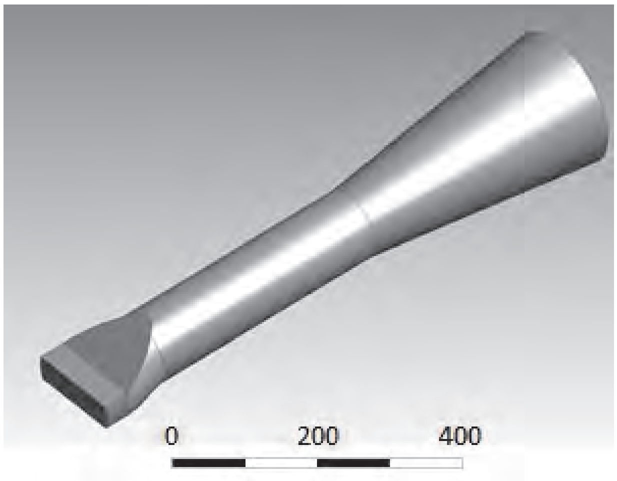

Fig. 2 Model of a nozzle (mm) [8]
Obr. 2 Model dýzy (mm) [8]

Pitot tube uses one inlet hole for total pressure sensing while the static pressure is measured in different position where the air is stationary. A simple example of the Pitot tube measurement is shown in Fig. 3. The measured differential pressure corresponds to the difference in levels Δh of the liquid in the U-tube which can be replaced by an electronic micro-manometer.

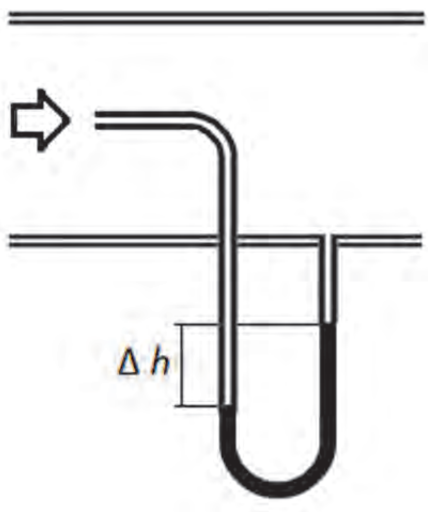

Fig. 3 Example of Pitot tube measurement [9]
Obr. 3 Příklad měření Pitotovou trubicí [9]

The Prandtl tube has one opening towards the fluid flow direction for measuring total pressure and several small static pressure sensing openings, located perpendicularly to the flow direction around the circumference of the tube at a certain distance from the tube tip.

Dimensions of the Prandtl tube used during the experiment are shown in Fig. 4. Outer diameter of the Pitot tube was 4 mm and internal diameter was 2 mm.

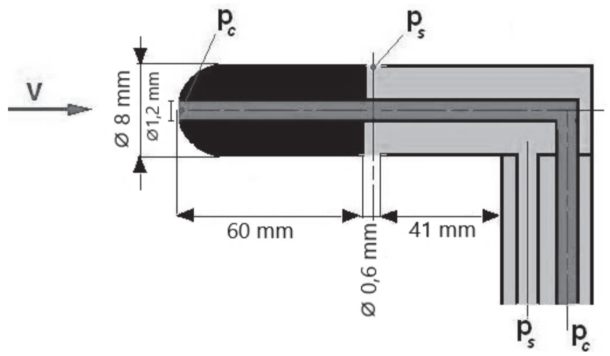

Fig. 4 Dimensions of Prandtl tube
Obr. 4 Rozměry Prandtlovy trubice

Velocity at a distance of 20 mm from the nozzle outlet orifice was measured and compared. The velocity dependence on a coordinate perpendicularly to the flow direction as well as the dependency of velocity on the distance from the nozzle orifice was measured.

In a real application, as the sensor moves along the conveyor across the individual air nozzles, the Pitot tube is not always co-linear with a flow direction. Angular deviation between the flow direction and the sensor axis may affect the data [10]. For that reason, the effect of the sensor angular deviation from the local flow direction was evaluated as well.

Differential pressure was measured by a differential pressure gauge. Dynamic pressure is derived from the total and static pressure. Micro-manometer Airflow APM 5000, micro vane anemometer Testo 445, probe 0635.9540 with measurement range 2 – 60 $m \cdot s^{-1}$ and data-logger Grant 2020 were used.

3. Measurements results

A comparison of the velocity change relative to the velocity at the nozzle outlet in dependence on a distance from the outlet obtained by means of a Pitot tube and a micro vane sensor is shown in Fig. 5.

The difference in measured values by micro vane anemometer falls into the range of device accuracy of ± (0.2 $m \cdot s^{-1}$ +1 % of m.v.).

A comparison of all three sensors during 15 measurements at a constant position while decreasing air flow velocity is shown in Fig. 6. The values measured by Pitot and Prandtl tubes were close. Their difference from micro vane sensor data is close to linear function and in praxis can be corrected by calibration.

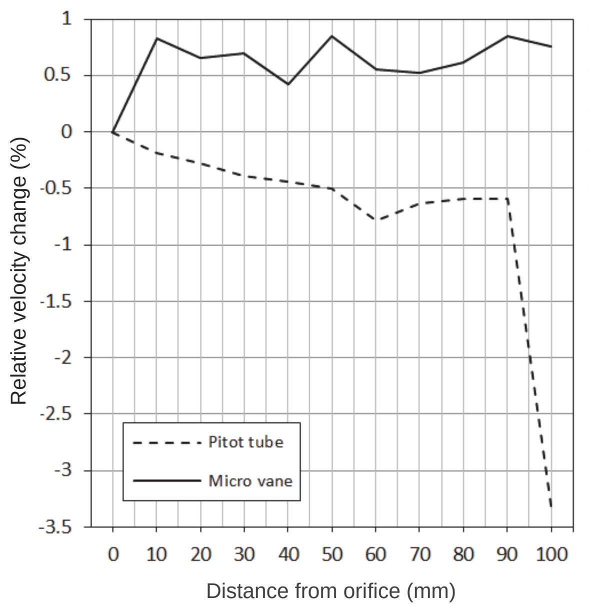

Fig. 5 Velocity change relative to the velocity at the outlet in dependence on a distance from the outlet
Obr. 5 Relativní změna rychlosti vůči rychlosti na výstupu dýzy v závislosti na vzdálenosti od ústí dýzy

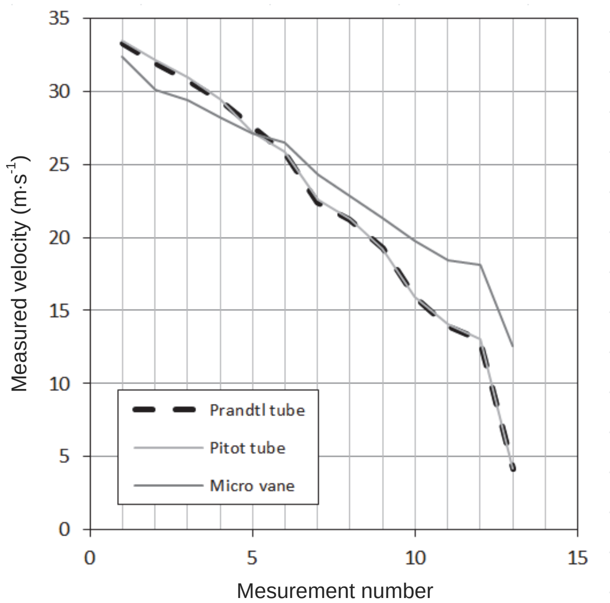

Fig. 6 Comparison of micro vane anemometer, Pitot tube and Prandtl tube
Obr. 6 Srovnání vrtulkového anemometru s Pitotovou a Prandtlovou trubicí

Pressure decline with an increasing distance from the outlet was investigated using the Pitot tube for different velocities and results. Obtained trends seem to be consistent and promising for further use. Up to a distance of 9 cm from a nozzle orifice, there is only a negligible drop in obtained differential pressure for all three initial air flow velocities, see Fig. 7.

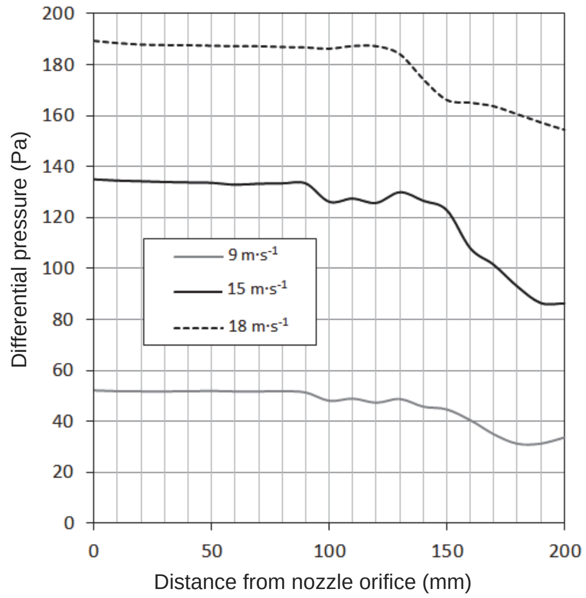

Fig. 7 Differential pressure dependence on a distance of the Pitot tube from the nozzle orifice
Obr. 7 Závislost diferenčního tlaku na vzdálenosti Pitotovy trubice od ústí dýzy

The sensor angle deviation sensitivity was evaluated for Pitot and Prandtl tubes for velocity of 18 m·s^{-1}. Measured data from the Pitot tube vary less than that of the Prandtl tube. However, for both sets of data, the angle of 15° represents a limit for accuracy. However, the Pitot tube is less affected by increased angle deviation in comparison to the Prandtl tube. Data are presented in Fig. 8.

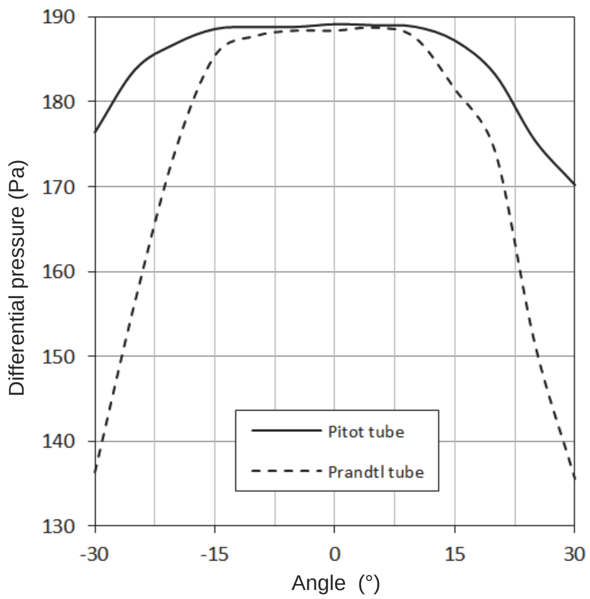

Fig. 8 Angle deviation sensitivity for Pitot and Prandtl tubes
Obr. 8 Citlivost na úhel náklonu Pitotovy a Prandtlovy trubice

The angle deviation sensitivity for two different velocities was measured by the Pitot tube. Measurement confirmed previously obtained results. Differential pressure decline can be neglected up to the angle of 15°. However, with increased airflow velocity the concavity of the curve increases, see Fig. 9.

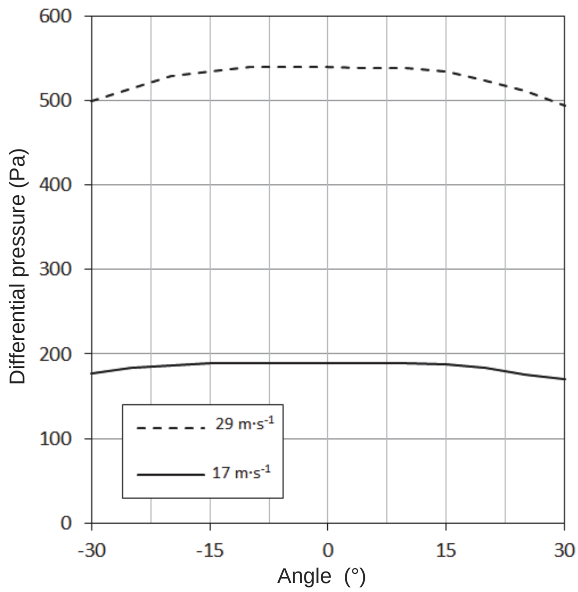

Fig. 9 Pitot tube differential pressure dependence on sensor angular deviation at airflow velocity of 17 m·s^{-1} and 29 m·s^{-1}
Obr. 9 Změna diferenčního tlaku Pitotovy trubice pro rychlosti 17 m·s^{-1} a 29 m·s^{-1} v závislosti na náklonu snímače k ose proudu

In order to define the sensitivity of the Pitot tube to the angular deviation from the flow direction, a dependence of relative measured velocity change on the angle was evaluated for velocities of 18 and 30 m·s^{-1}. Velocity change relative to the velocity measured while the sensor is parallel with air flow is shown in Fig. 10. Up to angle of 15°, the relative change of measured velocity is below 1 %, however at the deviation of 30° relative velocity change is higher than 5 %.

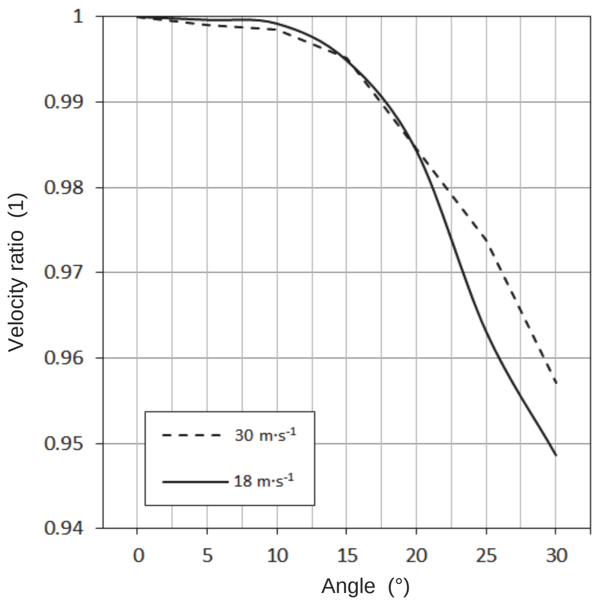

Fig. 10 Ratio of measured velocity to velocity in the direction of flow depending on sensor angular deviation
Obr. 10 Poměr naměřené rychlosti k rychlosti ve směru proudění v závislosti na úhlové odchylce Pitotovy trubice

Experiments indicated that the use of the differential pressure probe is a suitable choice not only for the resistance to mechanical damage but also in terms of the measurement results.

To confirm that the flow is fully developed in a virtual plane perpendicular to the flow direction at a distance of 25 mm from the outlet of the nozzle and that the previously measured values are not affected by uneven velocity field, a velocity profile across the nozzle outlet plane was measured. It suggests that the flow is fully developed, as shown in Fig. 11. The velocity profile is close to linear and declines only near the walls.

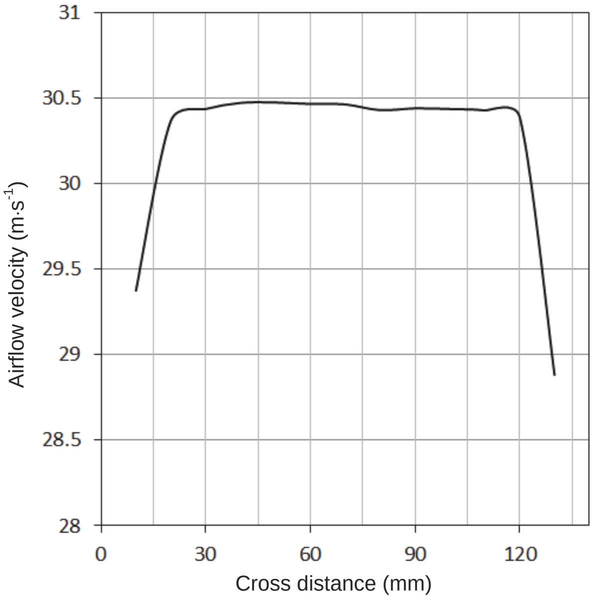

Fig. 11 Measured nozzle outlet velocity profile
Obr. 11 Naměřený rychlostní profil u výstupu z dýzy

4. CFD simulation

The airflow from the nozzle was also examined via CFD simulation with regards on mesh size, turbulence models and turbulence intensity level at the inlet [11].

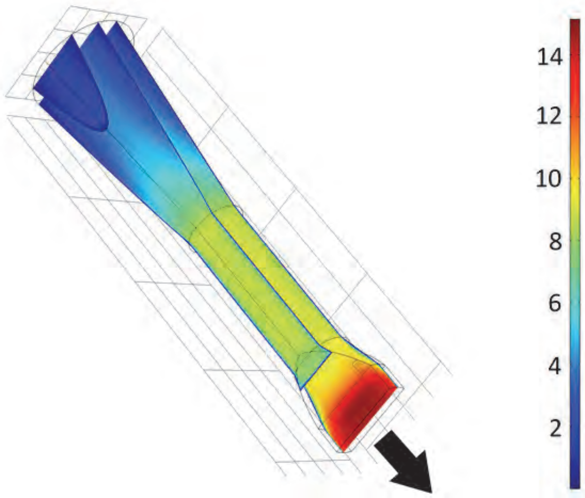

Fig. 12 Airflow velocity in the nozzle model ($m \cdot s^{-1}$)
Obr. 12 Rychlost proudu vzduchu v modelu dýzy ($m \cdot s^{-1}$)

Computer simulations provide numerous computing methods that can lead to significantly different results. A 3D model of a nozzle was created, and six simulations with different calculation models were executed in order to obtain a comparison with measured results. A simulated layout of airflow velocity inside the nozzle is shown in Fig. 12.

The following turbulent models were used: k-ε-realizable and RNG, Spallart-Allmaras, k-ω-realizable, Reynolds-Stress SST and DES.

Various turbulent models exhibit similar results. Differences are notable in computational time. Spalart-Allmaras model is a single equation model, and k-ε and k-ω are two equation models (an equation is added due to turbulence to Navier-Stokes equations in the RANS method).

The shape of velocity profiles for each computational method obtained via CFD simulation reliably represent measured data. A comparison of computed and measured velocity profiles is in Fig. 13. The horizontal axis represents a ratio of a distance from the nozzle axis in the direction of the outlet longer dimension to half of the nozzle outlet shorter dimension. The closest values to measured data were obtained by both *k-ε* models and DES model.

The measured velocity profile reaches higher values when compared to simulation results. However, the velocity difference in the nozzle axis is only 1.24 $m \cdot s^{-1}$, which represents 4.4 % for the k-ε-realizable model. The error is the sum of the model error and the uncertainty of the measurement including possible inaccuracy of the air parameters.

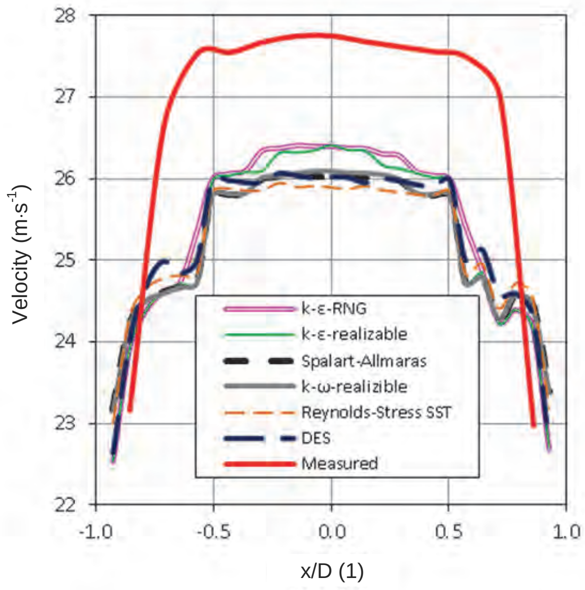

Fig. 13 Velocity profile of CFD simulation and measured results
Obr. 13 Rychlostní profil CFD simulace a výsledků měření

Conclusions

For practical use in real conditions of hot rolling production, the simple Pitot tube as a sensor offers unique advantages as it features low cost, high reliability, simplicity, low wear and minimal maintenance demands. It also delivers results very similar to Prandtl tube.

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It was also found out, that Pitot tube can provide accurate results up to its 15° angular deviation from the airflow direction.

A comparison of measured data with CFD simulation showed a velocity difference of 1.33 $m \cdot s^{-1}$ in the nozzle axis, which represents the relative error of 4.8 % for the k-ε-realizable model. CFD simulations confirmed that the airflow is fully developed in the plane perpendicular to the nozzle axis at a distance of 25 mm from the nozzle outlet.

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Noc vědců letos na symbolické téma - sto let české vědy

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Noc vědců je akce pro veřejnost, která vznikla z podnětu Evropské komise v roce 2005 a jejím posláním je popularizace vědy a osobností vědců. Jeden den v roce jsou na stovkách míst v Evropě ve večerních a nočních hodinách zpřístupněny univerzity, vědecká a výzkumná pracoviště, science centra a další pracoviště, ve kterých se zdarma konají komentované prohlídky, populárně vzdělávací přednášky, workshopy, experimenty, vědecké show, hudební vystoupení apod. Cílem Noci vědců je bořit mýty o vědcích a vědkyních jako lidech zavřených v laboratořích a ukázat nejširší veřejnosti, že vědci jsou „obyčejní lidé“, kteří vykonávají práci přínosnou pro každého z nás, dokážou ji poutavě představit, ale také se dovedou bavit. Vědci přednášejí široké veřejnosti, předvádějí zábavné pokusy, organizují soutěže, a to vše při aktivním zapojení návštěvníků.

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