EXPERIMENTAL VERIFICATION OF THE FEASIBILITY OF THE CFD APPROACH IN AN AIR-KNIFE

by

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Air knives with very different nominal values are used for various purposes in the industry. The uses of air knives include the painting and coating stages of automobile semi-finished products, as well as many stages related to food production. One of the important sectors among these is the continuous hot-dip galvanizing process, which is a coating technique in the steel industry. In addition, the chemical coating process on paper as a very thin layer is another research topic. The most critical process needed in these sectors is to ensure a homogeneous air-flow at the expected air speed of the air-knife. These determine whether the coating on the steel or the chemical layer on the paper is homogeneous at the desired thickness. In this study, it is aimed that the air-knife can reach the expected values (speed and homogeneous distribution) with the expected tolerances, the shortest time, cost, and the least production process error. First, a design has been made so that this knife can blow air at the desired speed and homogeneously. For this, the most appropriate modeling and design values were created and analyzed with the CFD. The analysis and evaluations of the design were confirmed as a result of the measurements made on the prototype. This study shows that the inclusion of this type of modeling and analysis in the rapid product development process has an important role in minimizing cost and time.

Key words: *air-knife, CFD analysis, prototype test*

Introduction

Air knives are used in different fields of industry. Air knives are frequently used in a variety of industries like automobile, chemistry, metal processing, packaging, paper printing, and similar. Air knives are chosen for many processes due to features like low cost, regular air-flow, simple structure, easy installation, effective reduction of energy loss, and similar features. They are frequently used for washing and drying, and cleaning of dust, industrial residues, and fluids after product filling processes. Additionally, they are used to provide humidity to foods in the food sector [1-3]. Air knives are commonly used in the continuous hot dip galvanizing procedure, a coating technique in the steel industry [4-11]. The paper industry is one with effective use of air knives in the thermal paper production process where a very thin layer of chemicals is spread on paper [12].

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Additionally, use for thermal paper has significant economic dimensions currently. In addition to the economic dimension of this process, there are environmental effects due to the chemicals used. For this reason, it is necessary to complete all steps with the most economic and efficient processes from use in thermal paper to production.

In the production of thermal paper, the distribution of the chemicals transferred to the paper surface in the desired amount and homogeneously on the paper surface depends on the air velocity, homogeneous distribution and form of the air-knife. Likewise, in the continuous hot-dip galvanizing process, which is a coating technique in the steel industry, air knives are used to provide the desired thickness and homogeneous distribution of the coating on the steel. Here, the speed and homogeneous distribution of the air coming out of the air-knife are important. Considering similar situations, the air-knife used at this stage should meet the experience-based features in the sector.

Achieving success depends on determining the basic features of the system element with design and analysis software and manufacturing it in accordance with these design and analysis, instead of many trials and error.

In order to complete this process efficiently and rapidly with least deviation from the targeted values and costs, the first step is to use the available design and software facilities. Continuing from this point, the production of a prototype based on design and analyses may be assessed as the second step. Comparison of measurement values obtained from the prototype is a step before mounting this element into the main system. The content of this study comprises explanations of these steps and sections comparing results obtained from these processes.

The subject that has been widely discussed in the literature for the air-knife is related to the galvanization coating. There are not many studies (articles) about chemical coating on thermal paper using air-knife. The subjects that examine the internal air-flow of the air-knife [3, 12] are also among the less studied subjects. The following literature can be evaluated when considering the contents that are fundamentally like the subject of this study.

Researchers made a variety of recommendations to prevent errors and control the coating thickness for zinc-coated surfaces in continuous hot dip galvanizing processes [4, 6, 8, 10]. So *et al.* [4], analyzed surface flaws (which called sag lines) on steel sheet surfaces and developed a new model to predict the variation in coating thickness. They performed 3-D CFD simulations. Another study by Ahn and Chung [6], recommended a configuration to prevent flaws on the edges of steel strips, edge overcoating (EOC) by simulating a 3-D unstable compressible turbulent flow area. Inaccurately determined air-knife parameters caused bouncing off the strip edge with negative effect on performance of the galvanizing process and product quality. Lee *et al.* [8] performed an experimental study to research the efficacy of a Coanda nozzle to reduce the edge overcoating problem. They designed a variety of nozzle types to find the most suitable configuration for the Coanda nozzle. With the results, they showed the Coanda nozzle effectively reduced the bouncing problem and caused improvements in the whole galvanizing process. Yoon and Chung [10], proposed a new double air-knife system in studies providing both better zinc removal capability and reducing stain (flaw) appearance.

Bao *et al.* [9] completed a study about applying protective zinc coating with air-knife blowers with numerical simulation of air-flow in 2016. This study also analyzed the effects of process parameters like air pressure, air blowing interval, knife opening and angle on coating thickness.

Tamadonfar *et al.* [7] and Soufiani *et al.* [5] performed a variety of studies to control the coating thickness of zin with the gas jet wiping process using an air-knife system in the continuous hot dip galvanizing process. These researchers investigated a new configuration with numerical simulations for a multi-slot air-knife as an alternative to the single-slot air-knife commonly used to control coating thickness in galvanizing processes for steel sheet products.

Among researchers performing simulation studies for internal flow area in air knives, Polanco *et al.* [3] stated that simulations contributed to estimations made about reducing unwanted effects in operating conditions during industrial processes. They showed that there was a smoother speed contour and reduced turbulence level and relational effects in the flow with changes to the geometry of the air-knife in drying systems.

Chen *et al.* [12] applied real conditions to define different boundary conditions for the internal flow area in the air-knife. For numerical simulation of the internal air-flow in the air-knife, they used FLUENT software for fluid dynamics. In the study, they found a parameter affecting the quality of air knives was the inhomogeneity of air-flow direction and velocity at the air-knife outlets and they presented an optimal model with two outlets, instead of the three generally used. Additionally, they showed that the flow area in the air-knife was largely affected by the guide plates and thus, internal flow area of the air-knife became uniform with the optimum design.

Achieving success depends on determining the basic features of the system element with design and analysis software and producing them in accordance with these designs and analyzes instead of many trials and error. To realize this process efficiently, quickly and with the least deviation and cost from the targeted values. Using existing design and software facilities is the first step. Following this, prototype production based on design and analysis can be considered as the second step. Comparing the measurement values obtained from the prototype is the first step before assembling this element to the main system. The explanation of the steps towards this and the sections in which the results obtained in the processes are presented and compared constitute the content of this study.

Numerical model

Normally, air knives have a broad body with different inlets and long thin outlets. This creates a complicated flow inside and a complicated downward jet flow at the outlets. Both situations were investigated with calculation methods using a 3-D approach for the internal flow and a 2-D approach for external flow. In this study, the geometric shape of the manufactured air-knife and experimental test rig for the analyses performed can be seen in fig. 1.

The air-flow within the air-knife is assumed as stable and incompressible flow. Properties of air, such as viscosity, density and thermal conductivity are assumed to be fixed. The FLUENT 19.2 commercial program was used for numerical simulation of the internal air-flow in the air-knife.

Air-flow can be represented by the Navier-Stokes equations, which include the mass and momentum balance equations. These equations in Cartesian co-ordinates are given in vector form by eqs. (1) and (2). The energy equation with the assumption of incompressible flow is not included in this study.

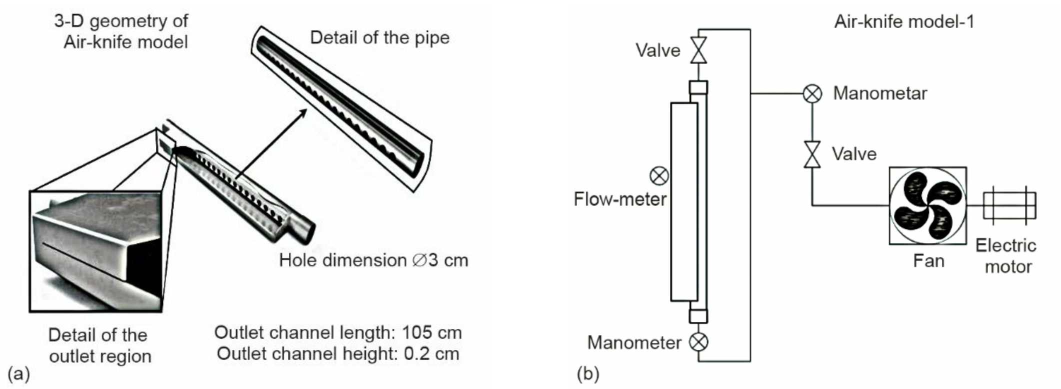

Figure 1. (a) Details of the air-knife model and (b) schema of the experimental set-up

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{\mathrm{V}}) = 0 \tag{1}$$

Momentum equation

$$\frac{\partial}{\partial t}(\rho \vec{\mathrm{V}}) + \nabla(\rho \vec{\mathrm{V}}\vec{\mathrm{V}}) = -\nabla P + \nabla(\vec{\tau}) + \rho \vec{\mathrm{g}} \tag{2}$$

The pressure in the cavity within the air-knife structure influences the acceleration and speed of the air. For this reason, to guarantee the equal distribution of flow at the outlet, it is necessary to provide equal and stable pressure distribution at the outlet. In the study, FLUENT 19.2 version was used to solve the flow area simulation for the air-knife. Generally, air knives are structures with complex geometry. There is a turbulent air-flow in the working cavity of the air-knife. Two equations k-ω and shear stress transport (SST) turbulence model were used to capture turbulence properties [13-16].

Computational domain and mesh

As seen in fig. 2, the 3-D analysis model began by modeling from the final points of measurements during experimental studies. Again, in order to obtain speed and pressure values at the air-knife outlet, it was also modeled and analyzed in 2-D on the XY plane with the Cartesian co-ordinate system.

For analysis models, mesh independence tests were performed many times and it was observed not to affect results. Approximately 10 M mesh was used for 3-D analyses and 500 K mesh used for 2-D analyses. Figure 3 shows a section of the mesh structure prepared for 2-D analysis. Finally, for 2-D mesh quality, the skewness, orthogonal quality, aspect ratio and element quality values were checked. These values were 0.29, 0.73, 3.77, and 0.73, respectively.

Simulation parameters

When determining the air-knife inlet input values, pressure values measured with manometers during the experimental studies were used. The manometer locations are given in

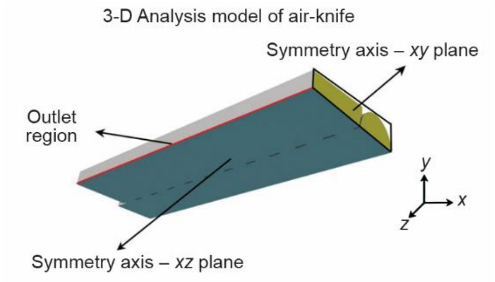

Figure 2. Explanation of 3-D CFD analysis of the model

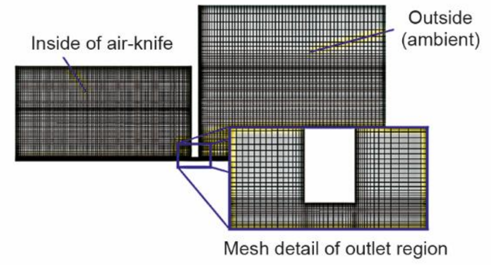

Figure 3. Details of 2-D mesh

fig. 1 at the outlet of the feed fan and inlet to the air-knife. As two manometer measurements were made, the friction loss value in the system (2-inch, 4 m ISO 1403/type1 pipe) was confirmed with analytic and experimental results and this was 2741 Pa. As the other manometer measurement value at the fan outlet was 6559 Pa, the pressure value at the air-knife inlet was calculated and confirmed as 3818 Pa. Due to the location of the manometer, the pressure loss due to sudden expansion at the air-knife inlet was calculated analytically and subtracted from the loss value read on the manometer. The calculated sudden expansion pressure drop value was 341 Pa. Thus, the pressure value to be used in 3-D analysis for the air inlet region was calculated as 3477 Pa.

The physical properties of air used in model solution (viscosity μ and density ρ) were taken as 1.818×10^{-5} kg/ms and 1.204 kg/m^3, respectively, according to the mean temperature of the experimental environment of 20 °C.

Experimental set-up

The experimental set-up for the experimental studies and to take measurements is shown in fig. 4. The experimental studies used 120 cm long, 5.08 cm (2-inch) pipe containing 22 holes with 3 cm diameter at 5 cm intervals, as seen in fig. 2(a). Then, this 2-inch pipe was covered with 0.2 cm sheets. The air-knife outlets opened onto a 0.2 cm channel with 105 cm length. In addition, 2 ribs have been added to the air-knife in order to provide the necessary strength against internal pressure

In the experimental set in fig. 4, a 1.5 kW 3000 rpm radial fan was used to provide air-flow. Two 2-inch ball valves and a 4 m long ISO 1403/Type-1 plastic pipe with a 2-inch T junction pipe have been connected to both inlets of the air-knife. Measurements were made using two manometers (SEL TEKNO 6 mm HL/YS S09241) and one anemometer (CEM DT-8920 pressure & flow meter/Range 1.0-80.0 m/s) in the experimental set.

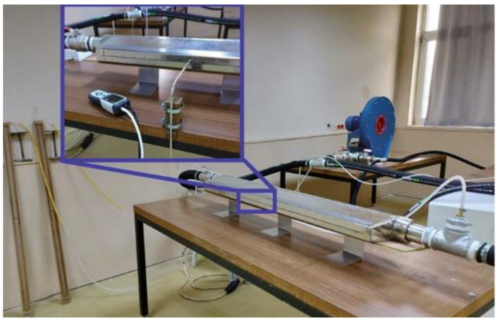

Figure 4. Photo of experimental set-up

Results and discussions

This section will present experimental and numerical results. Firstly, the validation of the model will be explained, then the performance of the air-knife under different boundary conditions will be assessed.

Model validation

The verification of the CFD model was carried out by comparing the air-knife outlet velocities obtained during the experimental studies, as seen in fig. 5. While the average velocity of the entire area in the air-knife outlet region was 55.76 m/s in CFD analysis, the average speed of 22 points obtained during the experimental studies was 52.63 m/s. The CFD model and the experimental results match each other and can therefore be used for air-knife performance comparisons.

On the other hand, the measurements in the outside region at the air-knife exit and the CFD analysis results were compared and verified. The analyzes for the outside region were made in 2-D in order to get fast results. Figure 6 shows the velocity distribution and vector contour of the air in the outside region after exiting the air-knife in the 2-D model.

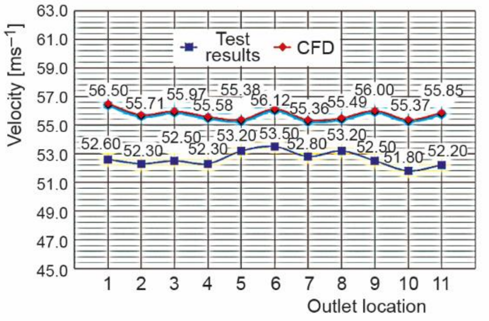

Figure 5. Comparison of outlet velocity of air-knife at different outlet locations

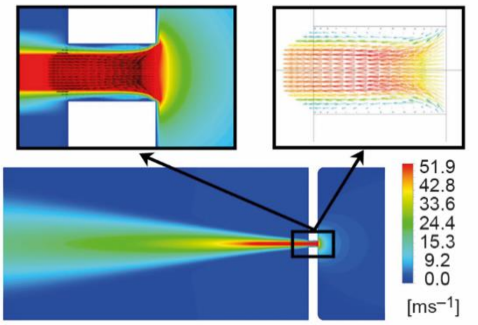

Figure 6. Velocity vector distributions in the outside region of the air-knife
(*for color image see journal web site*)

When determining boundary conditions for these analyses, 3-D analysis results were used. Figure 7 shows that measurement values obtained for the outside region and the CFD analysis results.

When the experimental studies and CFD analysis results are compared, it can be said that the CFD analysis results are a little high. However, when measurements with the anemometer were assessed for possible errors in environmental conditions and measurements, the analysis model, mesh structure and boundary conditions were appropriate to compare the air-knife performance.

One of the most important parameters in the air-knife set-up is the radial fan which determines the inlet pressure. Figure 8 shows the fan static pressure values that should be chosen according to the desired outlet velocity values.

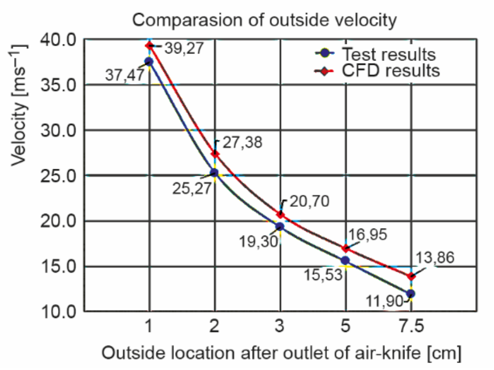

Figure 7. Velocity measurement values of the air-knife in the outside region and CFD analysis results

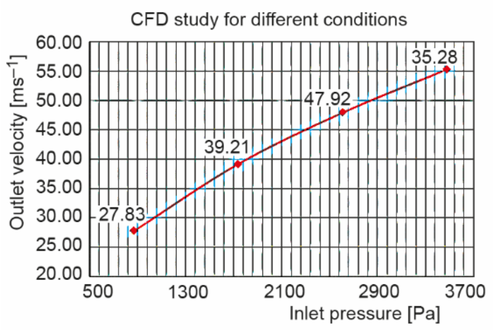

Figure 8. Fan static pressure according to outlet velocity

Conclusions

The CFD analysis shows that regular air-flow can be achieved in the designed model. Considering the design values reached in the CFD analysis, the measurements from the air--knife produced provided the design values. This clearly reveals the contribution of a successful design made before manufacturing in terms of time and cost.

As a result, rapid studies have been carried out with software-assisted design and simulation stages, which many well-established systems have been successfully using for many years. With this study, it has been shown that these stages can be successfully applied for the critical components of small and medium-sized enterprises. The obtained CFD and experimental measurement results reveal that to meet the needs of the sector, it is necessary to start with analyzes and there is a shorter way to meet the expectations.

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