Tomas Bata University in Zlín
Faculty of Technology

Doctoral Thesis Summary

Cooling of Aluminium Coils by Forced Ventilation with Outdoor Air

Chlazení hliníkových cívek nucenou ventilací venkovním vzduchem

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SUMMARY IN CZECH

Předmětem této disertační práce je chlazení hliníkových cívek nucenou ventilací venkovním vzduchem. Tento způsob umožňuje chlazení cívek po válcování za tepla přímo ve skladovacím prostoru, čímž se eliminuje nutnost jejich přemísťování a použití chladicích strojů.

Chlazení venkovním vzduchem pomocí mechanické ventilace je rozšířený způsob klimatizace, ale zřídka je používáno ve výrobě, kde požadavky na úroveň teploty jsou obvykle mimo dostupnou šířku pásma. Použitím volného chlazení se výrazně sníží příkon energie a tím i emise CO_2 pro proces chlazení.

Cílem této práce je navrhnout proces volného chlazení hliníkových cívek a zároveň lépe porozumět jejich tepelným vlastnostem. Je navrženo vhodné řešení proudění vzduchu v otevřeném skladu, které odpovídá obecným podmínkám výrobního procesu. Za tímto účelem byl vytvořen tepelný model cívek a stanoveno chladicí chování, jakož i požadovaný průtok vzduchu. V tomto procesu byl ověřen model a výpočty. Disertační práce poskytuje robustní výpočetní model pro stanovení chování cívek a vhodnou metodu návrhu proudění vzduchu.

SUMMARY

The subject of this doctoral thesis is the cooling of aluminium coils by forced ventilation with outdoor air.

This method enables the coils to be cooled directly in the storage area of the intermediate storage after hot rolling, thus avoiding the need for relocation and the use of refrigeration machines.

Free cooling with outdoor air, using mechanical ventilation, is widespread in the supply of air conditioning, but is rarely used in manufacturing, where the temperature level requirements are usually outside the available bandwidth. By using free cooling, the energy input, and thus the CO_2 emission for the cooling process is greatly reduced.

The aim of this thesis is to adapt the process of free cooling to the cooling of aluminium coils, and thereby to better understand the thermal properties of the coils. A suitable air flow solution in an open warehouse that fits to the general conditions of the production process is proposed. For this purpose, a thermal model of the coils is created and the cooling behaviour as well as the required airflow is determined. The model and the calculations are verified in the process. The thesis provides a robust calculation model to determine the behaviour of the coils and a suitable method of airflow design.

INTRODUCTION

Ecological and energy problems are increasing all over the world. The green movement is forcing the industry to make their products more sustainable and to think more and more about their eco-logical footprint to minimize the impact of the ongoing climate change. Papers, studies and journals like “Cleaner Production” show the importance of the sustainability.

Aluminium is a material that is indispensable or irreplaceable in many areas of application. Be it in the manufacture of light products such as cars, packaging, construction or applications in the electronics industry Thermal conductivity, low weight and durability are the main properties that make it so valuable for the use in many industries.

However, the extraction of aluminium is very energy intensive. Alumina processed from bauxite is the base material for the aluminium extraction, which is done by electrolysis. Both steps in the ex-traction consume large amounts of energy.

One of the further steps in the fabrication line to the finished product made of aluminium is the rolling of the aluminium blocks to sheet metal. Coming out of the hot mill, the sheet metal is wound up to a coil. Coils are the intermediate product for the production of aluminium sheet, strip and plate. Aluminium sheet, strip and plate are defined by national and international standards like DIN EN 485.

After coming from the hot mill, the coils have a temperature of approx. 350°C. The rolls are then cooled down to about 50°C for the next steps in production. Active cooling systems bring the rolled sheet aluminium down to the desired temperature. Then the coils are stored in a warehouse that functions as a buffer that optimizes the flow of material between the production steps. The remaining time of the aluminium drums in the warehouse is approx. 60 hours. The cooling is done before the coils go into storage to keep the necessary storing places at a minimum. In modern aluminium production, the buffer comes as a highly automated high bay storage facility.

Previous studies address the rolling of aluminium to sheet metal and in particular the thermal behaviour and the physical properties of the metal.

Other previous articles about metal coils deal with the thermal behaviour of steel and magnesium alloy in regard of free convection or other metals concerning products in electronics like heat exchangers and cooling coils or in solar thermal applications. There are also textbooks and research articles that focus on sheet metal and their thermal behaviour and the properties of heat transmission. However, these examples are mainly based on the effects in electronic applications, as mentioned before. No study or textbook covers the thermal behaviour of rolled aluminium as in transportation coils.

The cooling process is a step in the production line that plays a minor role in the energy consumption compared to the whole aluminium industry. Nevertheless, the cooling is highly power intensive and not very efficient. In addition, it is an inescapable logistic step to the production line.

To replace the active cooling by a more economical and environmental friendly method and eliminate the otherwise necessary logistic step of relocating the coils after cooling is the aim of this study.

Thus, this work introduces a method how to eliminate the relocation of the coils by leaving them in their designated storage place in the buffer and cooling the coils there on the spot by simply using outdoor air and still matching the given time limit. The study therefore closes the knowledge gap by developing a thermal model of the coils, calculating, based on the model, the required airflow and verifying it with test series.

1. STATE OF THE ART

1.1. Aluminium overview

1.1.1. Characteristics

Aluminium has a shiny, silver-white surface. It is a reactive, easily oxidisable element. Its great affinity for oxygen means that it immediately forms a very thin, natural layer (approx. 0.01 µm thick) with oxygen from the air. This passivates the underlying metal and protects it against further oxidization. Regardless of its low density, which is approximately a third of the weight of steel, aluminium has a high stability and tensile strength. With regard to the automotive and aircraft industry, this is a positive aspect. In addition, a number of aluminium engineering alloys have mechanical strength properties that partially exceed those of construction steel; thus, aluminium opens up a wide range of possibilities in the field of lightweight supporting structures.

Fig. 1-1 represents global aluminium consumption from 2016 to 2019, and includes a forecast through 2023. In 2019, global aluminium consumption amounted to some 60 million metric tons [1].

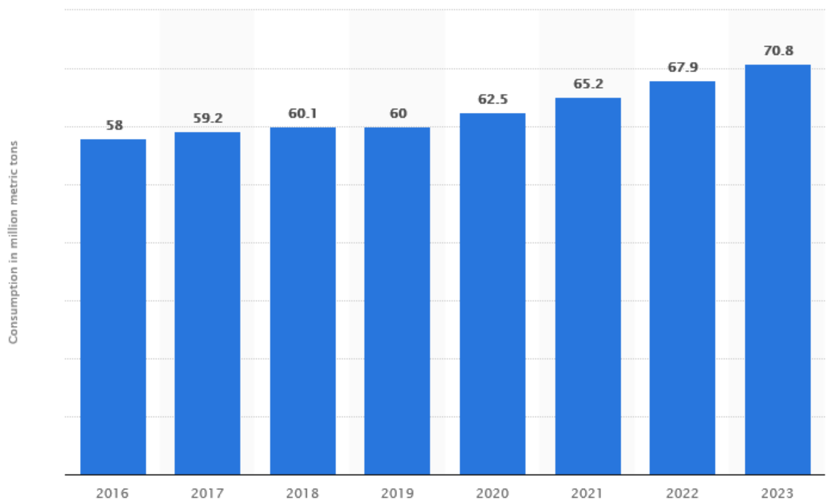

Fig. 1-1 Global aluminium consumption from 2016 to 2023 [1]

Aluminium is a base metal that is typically used in alloys with low quantities of other metals and can be found, among others, in automobiles, airplanes and drinking cans.

1.1.2. Aluminium extraction

Nowadays, the production of aluminium on an industrial scale takes place in two stages:

(1) Extraction of aluminium oxide (alumina) from bauxite
(2) Reduction of the oxide using fused salt electrolysis to extract the pure metal.

1.1.3. Processing of aluminium

1.2. Aluminium coil

Rolling aluminium is one of the principle ways of converting cast aluminium slab into a usable industrial form. The global production of rolled aluminium products more than doubled in the period from 2000 to 2017, from 12.9 to 26.2 million tons (+ 104 %), with a compound annual growth rate of 4.3 %. The total aluminium production worldwide was 63.697 million tons in 2019 [2]–[4].

According to these numbers, over 40 % of the global aluminium production is processed in the form of rolled metal for the end use in the various industrial sectors like packaging, aviation, automotive or construction.

1.2.1. Hot rolling

The metal slabs are heated to a temperature of approx. 525 °C to prepare the ingots for hot rolling [5]–[9]. After coming from the hot mill, the coils are still at a temperature of 350 °C [10], [11].

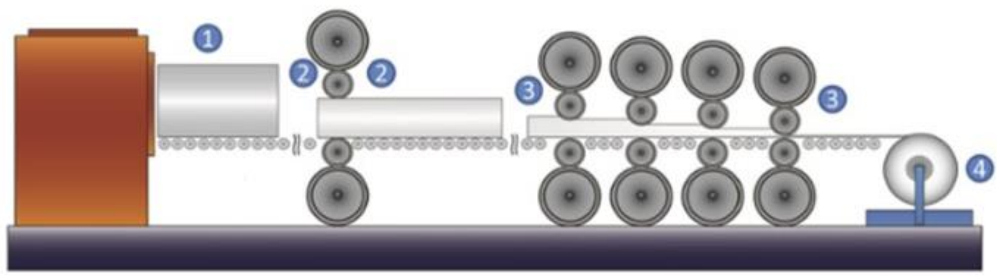

Fig. 1-2 Scheme of hot rolling (1: Ingot coming from a furnace, 2: Reversing/Roughing Mill, 3: Finishing Mill, 4: Coiler) [12]

The cold rolling necessary for some processes takes place after the coils have cooled down to 50 to 60 °C after hot rolling.

Coils typically have certain maximum dimensions. They have a length L, an outer diameter D_a, an inner diameter D_i and a number of layers depending on the thickness of the aluminium sheets, Fig. 1-3.

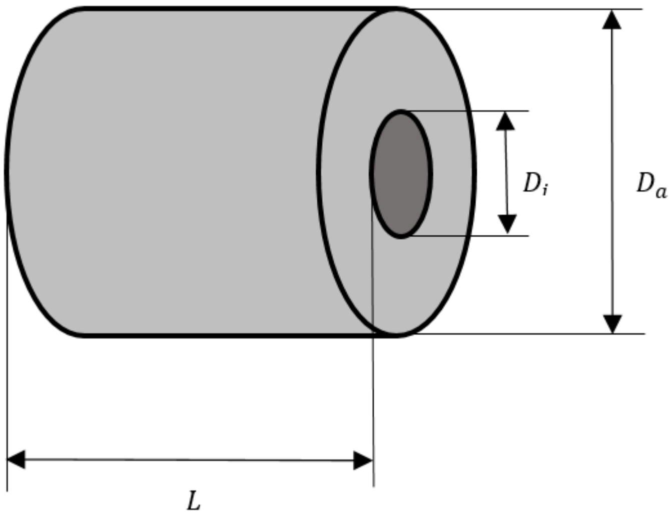

Fig. 1-3 Dimensions of aluminium coil

1.2.2. Storage and buffer

In order to prepare the metal for further processing such as cold rolling to adjust the mechanical properties to the desired parameters (e.g. strength), the coil must be cooled to the required temperature. For cold rolling, the temperature must stay under the recrystallization temperature of the metal at all times, which is approx. 150 °C for aluminium [13], [14]. During the cold rolling, the friction and pressure may raise the temperature by about 80 °C or more [14], [15]. Therefore, cold rolling is usually performed at room temperature (25 °C according to international standards [16]).

Additionally, there is another much simpler reason to cool the coils: the safety of workers. For example, it is simply too dangerous to prepare a metal drum for shipping when its temperature is 350 °C.

Therefore, in the aluminium industry, it is a standard practice to cool coils to a temperature between 60 and 50 °C before the drums are picked up from the storage buffer for further processing.

To cool the metal rolls and ensure that there are no water stains caused by the moisture´s condensation, the following methods are currently used [17]:

- Positioning the coil in a cooling chamber right after the hot mill

- Storing the coil in a warehouse with air conditioning
- Storing the coil in a warehouse, cooling by natural convection and radiation

The first two methods use a chiller attached to a forced ventilation system in a closed environment to cool the coils. In the first case it is also necessary to put the coils in a cooling chamber, and relocate them in the warehouse after the cooling process. The third method can be used if the warehouse as a production buffer is large enough to hold the coils for approx. 160 h until the coils are sufficiently cooled down [18].

In case of the first or the third method, depending on the location and surrounding climate, it is possible that heating of the storage is necessary to avoid water stains by moisture condensation (the temperature of the coil falls below the dew point) [17]. Transport and relocation are particularly critical.

For a current modern hot mill with an output of 650,000 tpy, an average coil weight of 20 t and 249 working days per year (in 2019), this adds up to 130 coils per day [19]. For this output, the warehouse must have 780 storage bins if there is no air conditioning and the coils must stay in their bins for 160 h, as mentioned above. The production capacity of a modern shows that active cooling instead of waiting for natural cooling could reduce the residence time of the coils and thus significantly reduce the size of the warehouse.

Fig. 1-4 shows a typical high bay storage. The metal drums are stored with spacing in a rack. The coils have minimum contact with the supporting structure. The surface area of the bearings is small compared to the surface area of the coils. Therefore, heat transfer by conductivity is assumed negligible.

Fig. 1-4 High bay warehouse for aluminium coils [20]

To apply an efficient airflow to the coils means to find a solution for a system that still allows access to the coils for relocating, and also effectively cools the drums.

Table 1-1 Overview of the recommended cooling methods employed in the aluminium industry [17]

Method	Power consumption, CO_2 output	Logistic effort	Indirect expense (storage cost, capital cost, etc.)
Active cooling (chiller, outside warehouse)	High power consumption leads to high CO_2 output	Relocation of coils necessary	Cost for chiller, cooling box
Active cooling (chiller, inside warehouse)	High power consumption leads to high CO_2 output	No relocation necessary	Cost for chiller, cost for air conditioning
Stationary cooling (natural convection / radiation inside warehouse)	No extra power usage, no extra CO_2 output	No relocation necessary	Cost for large warehouse, tied up capital

2. OBJECTIVES

The process of cooling the coils is a step in the production line that plays a minor role in the energy consumption compared to the whole aluminium industry [89]. Nevertheless, the cooling is highly power intensive, and therefore it can cause an additional carbon dioxide output [90]. It may introduce the incorporation of an extra logistic step to the production line, which then be-comes less efficient.

The subject of this doctoral thesis is to investigate the thermal behaviour of aluminium coils, determine the necessary parameters and find the feasible alternative cooling of aluminium coils by forced convection with outdoor air inside the warehouse. Until now, the coils have been cooled by natural refrigeration or by air conditioning in connection with chillers.

3. COOLING OF COILS

3.1. Theory of cooling

3.1.1. Heat transfer mechanisms

The relevant mechanisms of heat transfer concerning the aluminium coils are convection and radiation. The coil in the storage area has only little contact with the steel structure in relation to its total surface. Conductivity can be neglected.

The energy or heat content Q_{coil} of the aluminium coil can be expressed as:

$$Q_{coil} = m \cdot c_{Al} \cdot (T_{coil} - T_a) \qquad (1)$$

where c_{Al} is the specific heat capacity of aluminium, m stands for the mass of the coil, T_{coil} is the absolute temperature of the surface of the hot coil in Kelvin and T_a means the absolute constant ambient temperature also in Kelvin.

The heat transfer by convection $\dot{Q}_c$ is defined by equation (2):

$$\dot{Q}_c = h \cdot A \cdot (T_{coil} - T_a) \qquad (2)$$

where h is the heat transfer coefficient and A is the effective surface for the heat transfer by convection. In some textbooks, the variable of the heat transfer coefficient is named α.

The other mechanism of heat transfer, the transfer by radiation $\dot{Q}_r$, is formulated by Stephan-Boltzman-law:

$$\dot{Q}_r = \varepsilon \cdot \sigma \cdot A \cdot ({T_{coil}}^4 - {T_a}^4) \qquad (3)$$

where $\sigma = 5.67 \cdot 10^{-8}$ W m^{-2} K^{-4} is the Stephan-Boltzman-constant, A stands for the surface of the object and ε is the emissivity of the surface of the metal ($\varepsilon = 0.049$ for aluminium mill-finished [21]).

3.1.2. Cooling progression

Then the heat flow or change of the coil´s heat content $\dot{Q}_{(t)}$ is given by:

$$\dot{Q}_{(t)} = \dot{Q}_{(t=0)} \cdot e^{\frac{-t}{\tau}} \qquad (4)$$

where $\dot{Q}_{(t)}$ is the remaining heat content of the coil at any interval, $\dot{Q}_{(t=0)}$ is the heat content at the start interval, which is the sum of $\dot{Q}_r$ and $\dot{Q}_c$, t is the time of the interval.

Based on this and the fact that the only heat transfer mechanisms that are applicable to cooling the aluminium drums are convection and radiation, there are basically two possible approaches to cool the coils:

(1) Free cooling
(2) Forced cooling

3.2. Possibilities to model / simulate cooling

There are two necessary steps to approach the model and simulate the cooling of aluminium coils:

(1) Mathematical modelling and analytical simulation
(2) 3D modelling and numerical analysis with computational fluid dynamics (CFD) simulation software

The first step is important to build a solvable mathematical model of the aluminium coil.

In 2007, Saboonchi and Hassanpour [22] published a paper on the heat transfer of hot-rolled steel coils in multi-stack storing. In their study, the coil model was built in layers to have the simulation as close to the real coil as possible (Fig. 3-1).

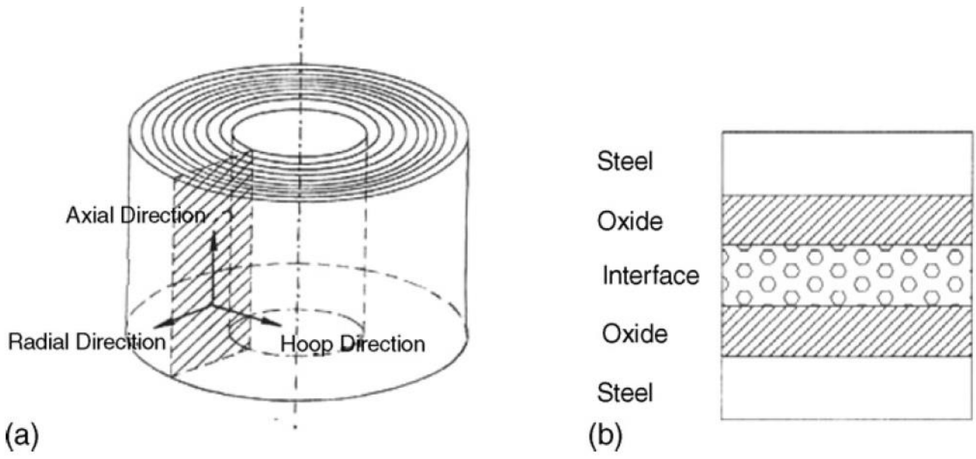

Fig. 3-1 (a) Cross-section of hot-roll coil; (b) thermal resistance of steel, oxide and intermediate layers in radial direction [22]

The calculations were done under two assumptions. One was that the layers in the coil have insulation as an interface in between them. The other was to neglect the interface layer and assume direct conducting surfaces between the steel strips. They measured four coils to validate their calculations and the mathematical model of the coil. The result showed that the interface layer can be really neglected and plays a negligible role in the thermal behaviour of the coils.

With these results, it can be assumed that it is a realistic approach to analyse and calculate the thermal behaviour of the aluminium coils with the basic equations from chapter 3.1. The coils can be considered to be made of solid aluminium. The layers and the possible thermal resistance between the windings can be neglected.

3.3. Mathematical modelling and analytical simulation

in respect to the above mentioned studies and the likely transferability to aluminium, the basic approach to modelling the aluminium coil was to take it as a hollow cylinder made of solid metal.

To create an analytically solvable thermal model of the coil, its surfaces had to be determined first. The next step was to find the average heat transfer coefficient for free convection as well as for forced convection in solvable approximations. Together with the different types of heat transfer, the cooling progression could be calculated in an analytical simulation.

3.3.1. Relevant coil surfaces

For the jacket surface A_j, the equation relates to the geometric properties of the metal tube.

$$A_j = L \cdot \pi \cdot D_a \tag{5}$$

where L stands for the length of the cylinder. For the inner surface A_i applies the same equation.

$$A_i = L \cdot \pi \cdot D_i \tag{6}$$

For the front face or lateral face of the cylinderA_l, the surface of the inner hollow cylinder must be subtracted from the entire circular surface.

$$A_l = \pi \cdot \left(\left(\frac{D_a}{2} \right)^2 - \left(\frac{D_i}{2} \right)^2 \right) \tag{7}$$

The total surface for radiation $A_{\Sigma r}$ is the addition of all the partial surfaces.

$$A_{\Sigma r} = A_j + A_i + 2 \cdot A_l \tag{8}$$

The surface $A_{\Sigma c}$ for free convection is the sum of the jacket surface and the two lateral surfaces.

$$A_{\Sigma c} = A_j + 2 \cdot A_l \tag{9}$$

The total surface $A_{\Sigma f}$ that can be used for forced convection specifically in the given case is an addition of the jacket surface, the inner surface but only one lateral surface:

$$A_{\Sigma f} = A_j + A_i + A_l \tag{10}$$

The reason for this is that no duct routing can be placed on the side of the aisle where the coil must be accessed by the stacker crane. This lateral surface faces away from the airflow and is therefore only minimally effected by it.

3.3.2. Convective heat transfer coefficient

Equation (2) shows that the heat transfer by convection depends only on the surface involved, the temperature difference, as the driving force of the transfer, and the heat transfer coefficient. The heat transfer coefficient in free and forced convection can be derived from the Nusselt number which is the dimensionless heat transfer index and is defined as:

$$Nu = \frac{h \cdot L_c}{k} \qquad \text{and resolved to h:} \qquad h = \frac{k \cdot Nu}{L_c} \tag{11}$$

where h is the convective heat transfer coefficient between the body and the fluid, L_c is the characteristic length and k is the thermal conductivity of the fluid.

For free convection the average Nusselt number is expressed as a function of the Rayleigh number Ra and the Prandtl number Pr, written as:

$$Nu_c = f(Ra, Pr) \tag{12}$$

Otherwise, for forced convection, the Nusselt number is a function of the Reynolds number Re and the Prandtl number:

$$Nu_f = f(Re, Pr) \tag{13}$$

For the description of forced and free convections, which are similar in their flow form, the following dimensionless numbers are used.

The Reynolds number essentially describes the flow form of forced convection:

$$Re = \frac{v \cdot L_c}{\upsilon} \tag{14}$$

with v as the flow speed, L_c being the characteristic length of the flow field and υ as the kinematic viscosity of the fluid.

Further, the Prandtl number mainly covers the substance properties in heat transfer for free and forced convection:

$$Pr = \frac{\upsilon \cdot c_p \cdot \rho}{k} \tag{15}$$

where υ is the kinematic viscosity of the fluid, c_p stands for the specific heat at constant pressure, ρ means the density and k the thermal conductivity of the fluid.

The Rayleigh number summarizes the material and the flow properties in free convection:

$$Ra = Pr \cdot Gr \tag{16}$$

where Gr, the Grashof number, indicates the flow with free convection:

$$Gr = \frac{{L_c}^3 \cdot g \cdot (T_s - T_a) \cdot \beta}{\upsilon^2} \tag{17}$$

here again L_c is the characteristic length of the flow, g means the acceleration due to Earth´s gravity, T_s and T_a stand for the surface temperature and the ambient temperature outside the contact layer, respectively, υ is the kinematic viscosity of the fluid, β means the coefficient of thermal expansion at constant pressure and is equal to approx. ${T_a}^{-1}$.

To calculate the heat transfer coefficient, a distinction was made between free and forced convection. Actually, forced convection is a mixed convection of free and purely forced convection. However, since forced convection clearly predominates, the proportion of free convection may be neglected [88].

3.3.2.1. Free convection

For free convection, in the case of the aluminium coil being basically a horizontal cylinder, the average Nusselt number can then be expressed as [23], [24]:

$$Nu_c = \{0.600 + 0.387\, [Ra \cdot f_1(Pr)]^{1/6}\}^2 \tag{18}$$

with $0 < Pr < \infty$ being the range of validity.

Here, the function $f_1(Pr)$ stands for the influence of the Prandtl number, which is:

$$f_1(Pr) = \left[1 + \left(\frac{0.559}{Pr}\right)^{9/16}\right]^{-16/9} \tag{19}$$

Together with equation (11) the convective heat transfer coefficient for free convection h_c could be analytically calculated for every interval of the temperature progression. This is necessary because, according to equations (16) to (18), the Grashof number and thus the Rayleigh number and in consequence the Nusselt number depend on the temperature difference, which changes with each interval. So in the case of the free convection, the heat transfer depends twice on the temperature difference between the hot body and the cooling fluid (equation (2)).

Likewise, the heat transfer by radiation is a function of the temperature difference (equation (3)) and must be recalculated for each interval. Therefore the time constant τ also changes with the progression of the coil cooling. The cooling rate slows down as the time constant τ increases.

3.3.2.2. Forced convection

For forced convection, there were three parts of the coil for which the average heat transfer coefficient had to be determined:

(1) the lateral area directed to the duct
(2) the jacket surface of the cylinder
(3) the inner tube of the coil

This was necessary because these three parts of the coil received the airflow with different velocities and volume due to the separate outlets of the air duct. The central outlet was aimed on the lateral surface covering also the opening of the inner cylinder. Then four outlets were determined to direct the air flow to the jacket surface of the coil. As a result, there is an average heat transfer coefficient for each of these three cases.

The heat transfer coefficient for forced convection, contrary to the coefficient in free convection, does not depend on the temperature difference between the body and the fluid but on the physical and thermal properties of the fluid on its velocity on the surface areas of the coil (equations (13) to (15)).

To come to a working thermal model of the coil, the cases had to closely resemble the already known special cases for calculating the Nusselt number [21], [25]. Therefore, the front side (lateral area) of the coil was to be considered an approximation of a plate with longitudinal flow. The airflow was regarded a deflection at the surface and there redirected parallel to the plane near the surface. The jacket surface of the cylinder was looked upon like a plate with longitudinal flow in respect to every one of the four outlets directed to this surface. Since the outer surface of the cylinder is not flat but curved, a trigonometric correction factor had to be used for the calculation. With these approximations, the aluminium coil was divided into four planes representing the jacket surface, one plane as the lateral area and a smooth tube for the inner hollow cylinder.

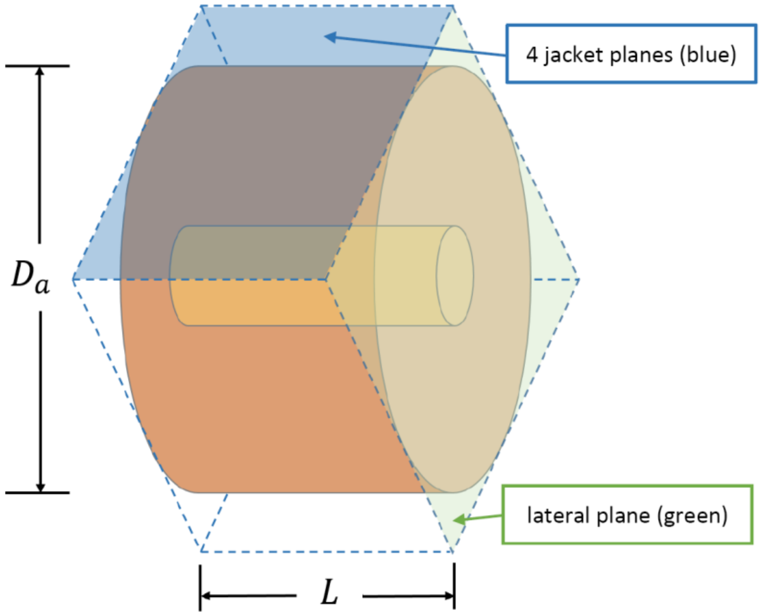

Fig. 3-2 Approximation coil model, orthogonal view, grey: coil and bearing, magenta: air duct, red: direction of air flow

Therefore, the describing equations for cases (1) and (2) are the same except the values of the air flow itself. The average Nusselt number for a flat plane with longitudinal flow with a turbulent boundary layer, cases (1) and (2), can be calculated as [21]:

$$Nu_{f(1),(2)} = \frac{0.037 \cdot Re^{0.8} \cdot Pr}{1 + 2.443 \cdot Re^{-0.1} \cdot (Pr^{2/3} - 1)} \tag{20}$$

The range of validity in this case is $5 \cdot 10^5 < Re < 10^7$ and $0.6 < Pr < 2 \cdot 10^3$. This equation covers both of the cases (1) and (2) but with different characteristics, like the characteristic length and speed of the airflow. The characteristic length L_c of the flow in these two cases is:

case (1): $L_c = D_a$, where D_a is the outer diameter of the coil (Fig. 1-3, Fig. 3-3)

case (2): $L_c = L$, where L is the length of the coil (Fig. 1-3, Fig. 3-3)

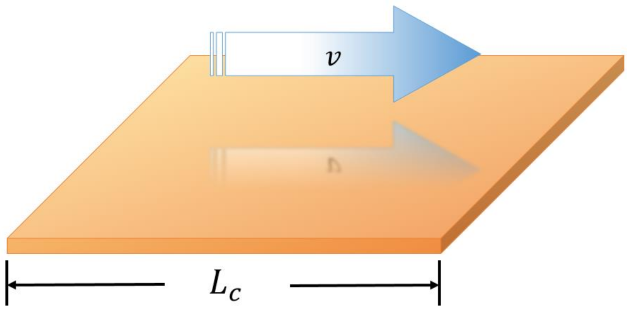

Fig. 3-3 Scheme of longitudinal flow along a plane (cases (1) and (2))

The average Nusselt number for the inner cylinder of the aluminium coil is similar to the one on the inside of a smooth metal tube, case (3), and can be expressed as [25]:

$$Nu_{f(3)} = \frac{(\xi/8) \cdot Re \cdot Pr}{1 + 12.7 \cdot \sqrt{\xi/8} \cdot (Pr^{2/3} - 1)} \cdot \left[1 + \left(\frac{D_i}{L}\right)^{2/3}\right] \tag{21}$$

with D_i and L as part of the coil´s dimensions (Fig. 1-3)., ξ is the friction coefficient of the smooth tube and follows the equation [26]:

$$\xi = (1.8 \cdot log_{10}Re - 1.5)^{-2} \tag{22}$$

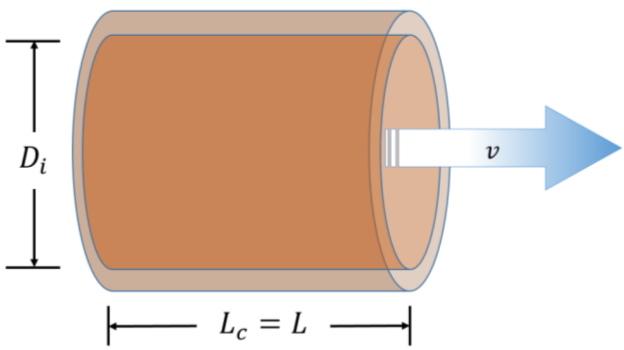

Fig. 3-4 Scheme of flow in smooth tube (case (3))

Together with equations (11), (20) and (21), the average heat transfer coefficients for forced convection could be computed for every case of the different air flow approximation $h_{f(1)}$, $h_{f(2)}$ and $h_{f(3)}$. Then these heat transfer coefficients had to be averaged over the coil in relation to the affected surface parts to get the overall average heat transfer coefficient h_f for forced convection.

4. METHODOLOGY AND CONTRIBUTION OF THE WORK

Table 4-1 Overview of goals, challenges and performed investigations

Investigation	Scientific goals	Technical, economic and ecological aspects
Alternative cooling method for aluminium coils with respect to:	Evaluation of a working thermal mathematical model of aluminium coils	Simplifying workflow in aluminium production
▪ **Using regenerative energy** ▪ **Reducing ecological impact** ▪ **Simplifying workflow**	Evaluation of airflow simulation in open warehouse environment	Provision of an alternative cooling method for aluminium coils
	Creating a calculation tool for predicting thermal behaviour of stored coils	Reduction of ecological footprint

5. DISCUSSION OF RESULTS

5.1. Experimental setup

In the experiments, two sets of coils coming directly from the hot mill were used for the measurements. The current production orders dictated the size and dimensions of the coils. All had an inner diameter of 600 mm.

Table 5-1 List of test coils characteristics

Coil No.	L [mm]	D_a [mm]	Weight [kg]	Sheet thickness [mm]
Small coils				
44/1	1650	1900	12,015	3
44/4	1650	1940	11,880	3
44/7	1580	2060	12,935	6
47/3	1580	2070	13,010	6
47/7	1580	2080	13,005	6
Large coils				
42/1	1940	2260	19,480	3
51/5	1940	2330	20,935	3
52/1	1940	2320	21,060	3
52/7	2040	2250	19,795	3
54/7	2040	2260	19,805	3
56/5	1940	2344	21,100	3

The control system placed the coils in a distributed pattern into the high bay storage for the setup of the series of measurements. The numbers corresponded to the location of the aluminium drums, e.g. coil 44/4 stood for column 44 and level 4 bin. The distribution had to avoid the mutual influence of the hot drums and to exclude the impact of the airflow by the design of the air duct.

Fig. 5-1 shows a photo of the real setting with round jacket outlets (a)). The right side of Fig. 5-1 (b)) is part of the construction drawing of the experimental setup showing the technical details. The magenta part of the drawing is the air duct with its outlet grids that eject the airflow onto the coil surfaces. The blue lines in Fig. 5-1 b) indicate the direction of the airflow. The magenta lines outline the air duct.

The aluminium coil with the No. 42/1 was used as a reference test subject. It was placed in the designated storage bin away from the other coils without forced air ventilation to verify the model simulation for free convection.

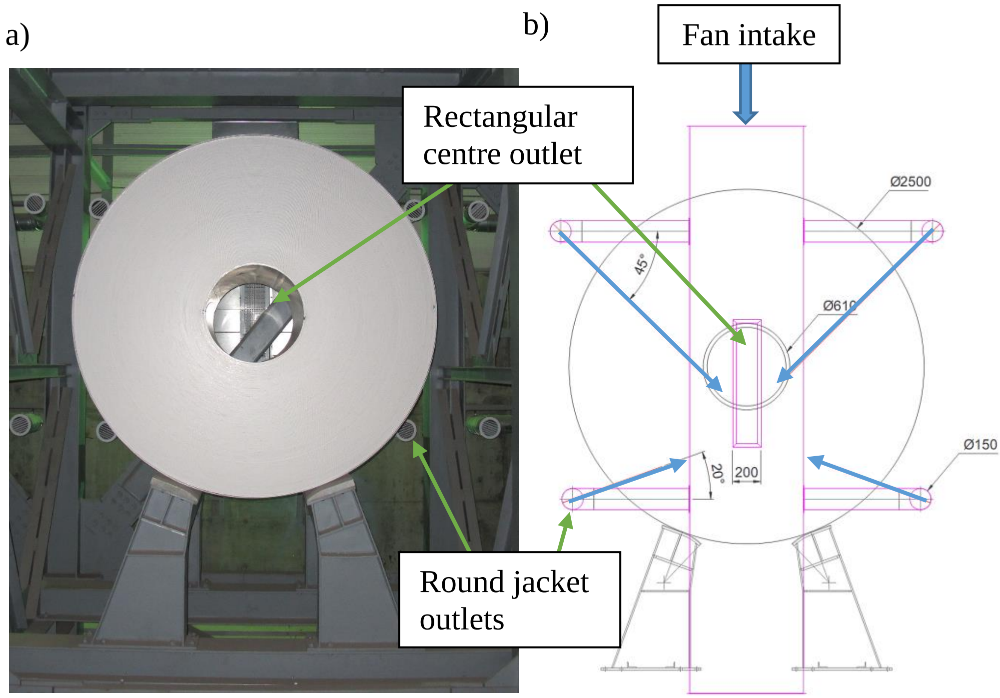

Fig. 5-1 Front view of experimental setup: a) real setup, b) technical details

So the small set of coils was measured 6 times and the large set 8 times. Only the reference coil for free convection coils be measured more often, 13 times.

The TC 301 model from Dostmann electronic with a surface sensor was used as the measuring device for the coil temperature. This model comes with an accuracy of ± 0.7 °C or ± 0.1 %. The air velocity and the volume flow were measured using the hand-held measuring device TSI9565 VelociCalc from Driesen+Kern with an accuracy of ± 1 % of the measured value. The control system of the storage facility logged the outdoor air temperature. A PT-100 sensor was placed in the air duct close to the ventilator (Fig. 5-1). The axial fan used for the setup was a R3G800-AQ03-XA model from ebm pabst company with an electrical power of 500 W for achieving the nominal airflow rate for one coil. The power consumption, which is electrical power in W multiplied with the duration in h, depends on the cooling time for the temperature limit.

Initial values and conditions for calculating the required heat transfer coefficients and the temperature progression are listed in Table 5-2.

Table 5-2 Initial Setup

Property	**Value**
Temperature of incoming coils [°C]	350
Temperature of outgoing coils [°C]	50
Average outdoor / supply air temperature [°C]	25
Average indoor air temperature [°C]	42
Coil weight [t]	26
Coil outer diameter [mm]	2,500
Coil inner diameter [mm]	610
Coil width [mm]	2,400
Target 1 for cooling in 45 h [°C]	60
Target 2 for cooling in 50 h [°C]	50

With the initial setup data and equations (5) to (10) the surface for radiation was computed to $A_{\Sigma\mathrm{r}}$ = 32.68 m² and convection to $A_{\Sigma\mathrm{c}}$ = 28.07 m². With equation (1), the heat content of the aluminium coil was Q_{coil} = 2,271 kWh.

5.2. Free convection – initial setup

With the indoor air temperature given in Table 5-2, the fluid properties of air for this temperature (Table 5-3) and the equations (11), (12) and (15) to (19), the heat transfer coefficient h_c for free convection could be calculated for each time interval. The values for h_c ranged from 9.00175 $\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$ in the first interval down to 3.94098 $\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$ after interval No. 161, when the coil´s temperature reached the target of 50 °C. The calculations were done with a safety margin of 10 %, e. g. to compensate for the accuracy of the approximations or other possible deviations.

For the first interval with free convection according to equations (2) and (3), the heat transfer by convection was computed to $\dot{Q}_{c(t=0)}$ = 77.86 kW and the heat transfer by radiation to $\dot{Q}_{r(t=0)}$ = 12.79 kW, which resulted in the total heat transfer $\dot{Q}_{\Sigma(\mathrm{t=0})}$ = 82.41 kW including the safety margin.

Using the initial conditions, the analytical simulation of the temperature curve (Fig. 5-2) showed that without additional measures, a coil needs more than 110 h to cool down to the first target temperature at the given average indoor temperature. For the second target, over 50 h more are required (over

160 h total). The graph also shows the trend of the heat transfer coefficient h_c during the cooling process.

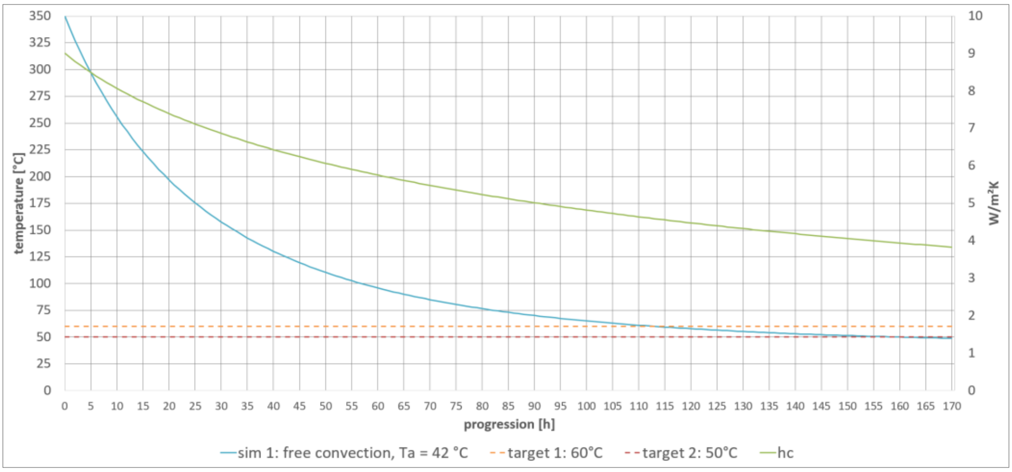

Fig. 5-2 Cooling curve, free convection, ambient temperature 42 °C

5.3. Forced convection – initial setup

For forced convection with the average outdoor respectively supply air temperature also given in Table 5-2, the air properties for this temperature (Table 5-4) and the equations (11), (13) to (15), (20) to (22) and the velocity of the airflow the average heat transfer coefficients could be calculated.

Table 5-3 Properties of air at constant pressure (1,013 mbar) at 25 °C [27]:

Symbol	Property	Value
υ	Kinematic viscosity [$m^2 \cdot s^{-1}$]	0.00001562
c_p	specific heat at constant pressure [$J \cdot kg^{-1} \cdot K^{-1}$]	1,007
ρ	Density [$kg \cdot m^{-3}$]	1.184
k	Thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]	0.02551

Table 5-4 Properties of air at constant pressure (1,013 mbar) at 42 °C [27]:

Symbol	**Property**	**Value**
υ	Kinematic viscosity [m²·s^{-1}]	0.0000175
c_p	specific heat at constant pressure [J·kg^{-1}·K^{-1}]	1,007
ρ	Density [kg·m^{-3}]	1.109
k	Thermal conductivity [W·m^{-1}·K^{-1}]	0.02699

For the first interval with forced convection according to equations (2) and (3), the heat transfer by convection was computed to $\dot{Q}_{c(t=0)}$ = 148.64 kW and the heat transfer by radiation to $\dot{Q}_{r(t=0)}$ = 12.97 kW, which resulted in the total heat transfer $\dot{Q}_{\Sigma(t=0)}$ = 146.92 kW including the 10 % safety margin.

The further simulation with the given conditions and the calculated heat transfer coefficients and airflows resulted in cooling of the metal drum up to the first target within 35 h and up to the second below 41 h, as shown in Fig. 5-3.

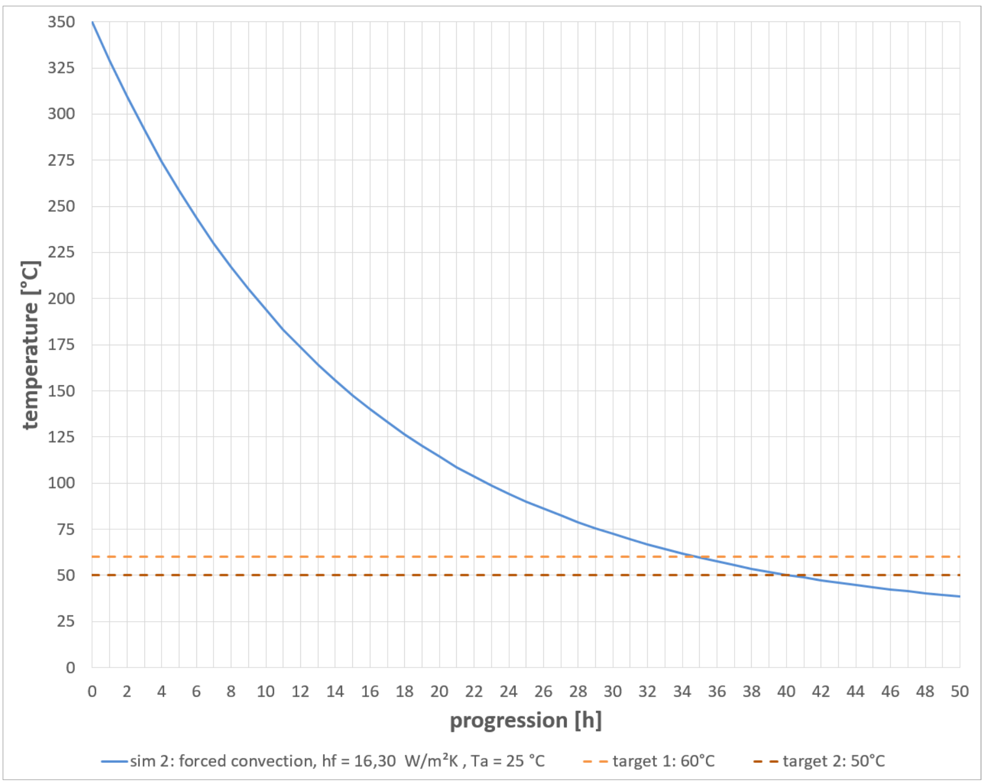

Fig. 5-3 Cooling curve, forced convection, supply air 25 °C

5.4. Analytical simulation and experimental results

5.4.1. Free convection

Coil No. 42/1 was used as a reference to verify the analytical model and simulation of free convection. It was placed in bin 42 level 1 and left there without ventilation to cool only by free convection. Table 5-5 shows the data of the measurements of this coil and the corresponding calculated temperature.

Table 5-5 Data of coil No. 42/1, average ambient temperature 32 °C

Time [h]	Measured Temperature [°C]	Calculated Temperature [°C]	Difference [°C]	Relative Difference [%]
0	260	260	0	0
1	252	252	0	0
16	172	164	8	5
18	167	155	12	8
21	154	144	10	7
24	142	135	7	5
41	102	97	5	5
45	94	91	3	3
52	83	81	2	2
62	72	71	1	1
93	52	52	0	0
108	45	46	-1	-2
125	44	43	1	2

Fig. 5-4 shows the curve of the simulation and the measurements together in a diagram. It shows that the measurements and the simulation curve are very close together. The match of simulation and actual measurements is obvious. The simulation and thereby the thermal model of the coil was validated for the case of free convection. Other possible disturbance variables played only an insignificant role in the result.

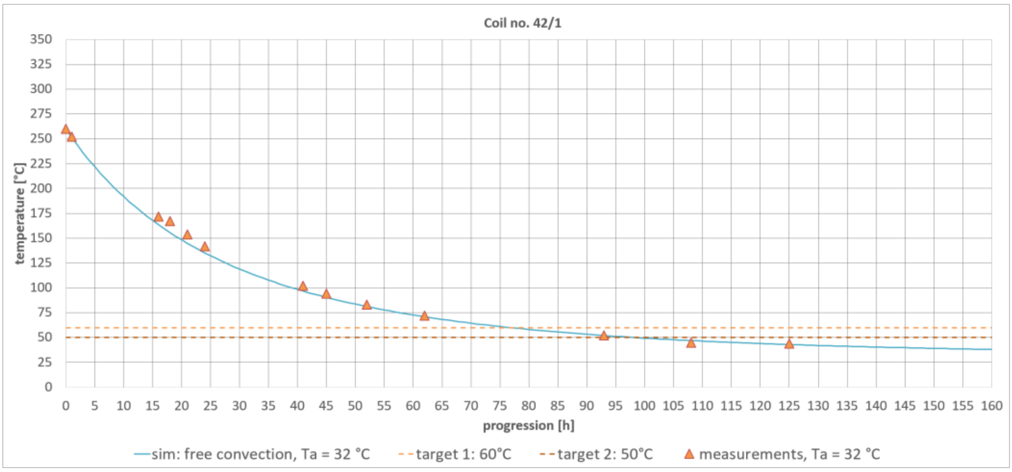

Fig. 5-4 Cooling curve of coil No. 42/1

5.4.2. Forced convection – exemplary validation

For the first comparison of the actual results with the simulations, two typical aluminium coils were chosen. One from the smaller coils from the group with the shortest length (No. 44/7, Fig. 5-5) and the other (No. 51/5, Fig. 5-6) from the set of large metal drums. The average outdoor and therefore supply air temperature was 28 °C for coil No. 44/7 and 29 °C for coil No. 51/5.

The results of the measurements as shown in,Table 5-6, Table 5-7 , Fig. 5-5 and Fig. 5-6 were close to the simulation. However, the following points must be observed. For both drums, the corresponding fan was running at the nominal load Due to the supply air grids, which were directed in a fixed manner towards the coil dimensions from the initial setup, Table 5-2, a part of the airflow passed the test objects with a reduced effect in the open environment of the warehouse. That could have affected the small coil in particular because it had the largest geometric differences compared to the metal drum in the initial data set that was used for designing the ventilation system. Nevertheless, it turned out that the air flow still reached the necessary speed to achieve a sufficient heat transfer coefficient value to dissipate the significantly lower heat content of the smaller coil. It was therefore cooled down within the required target cooling time and temperature (Fig. 5-5).

The number of layers, i.e. the thickness of the aluminium sheets showed no significant influence on the thermal behaviour of the test objects. The drums behaved as if they were made of solid metal.

Table 5-6 Data of coil No. 44/7

Coil No.	Average supply air temperature [°C]	Airflow speed coil centre [m·s^{-1}]	Airflow speed coil jacket [m·s^{-1}]	Heat transfer coefficient [W·m^{-2}·K^{-1}]
44/7	28	3.90	4.09	15.04
Time [h]	**Measured Temperature [°C]**	**Calculated Temperature [°C]**	**Difference [°C]**	**Relative Difference [%]**
0	320	320	0	0
1	284	300	-16	-5
17	120	117	3	3
22	94	91	3	3
25	83	80	3	4
41	47	45	2	4

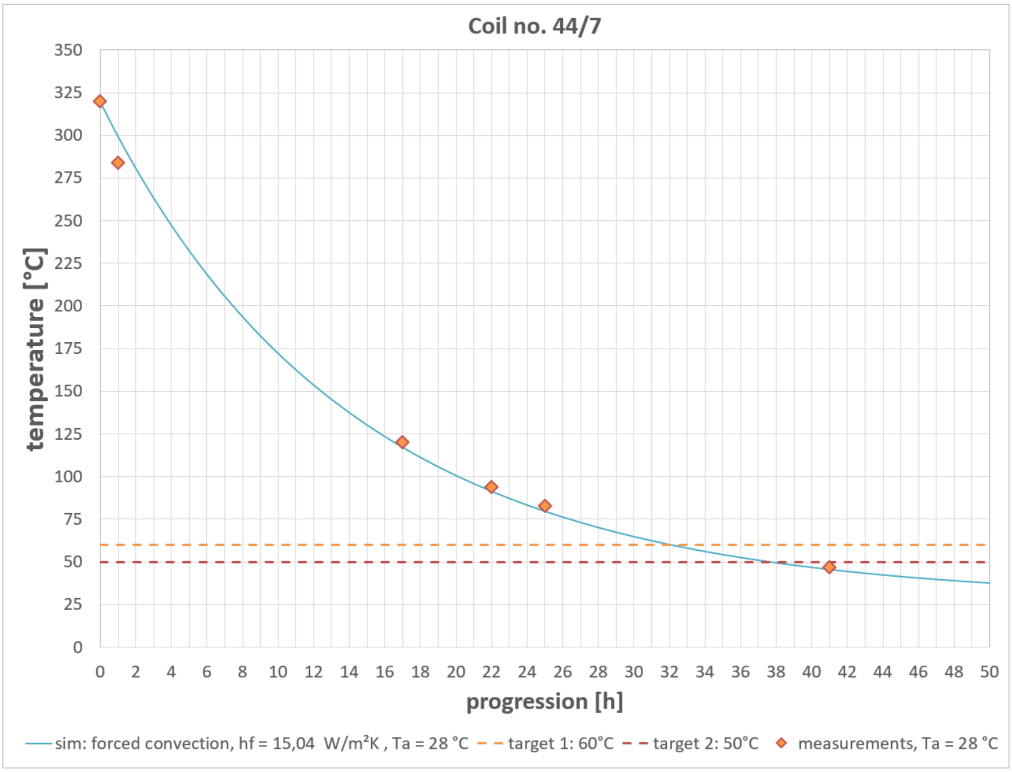

Fig. 5-5 Cooling curve of coil No. 44/7

A similar situation was experienced with coil No. 51/5, where the achieved, as shown in Table 5-7 and Fig. 5-6.

Table 5-7 Data of coil No. 51/5

Coil No.	Average supply air temperature [°C]	Airflow speed coil centre [m·s^{-1}]	Airflow speed coil jacket [m·s^{-1}]	Heat transfer coefficient [W·m^{-2}·K^{-1}]
51/5	29	4.29	4.34	15.19
Time [h]	**Measured Temperature [°C]**	**Calculated Temperature [°C]**	**Difference [°C]**	**Relative Difference [%]**
0	260	260	0	0
1	248	247	1	0
16	119	120	-1	-1
18	105	111	-6	-5
22	94	94	0	0
24	86	87	-1	-1
42	48	50	-2	-4
46	44	46	-2	-4

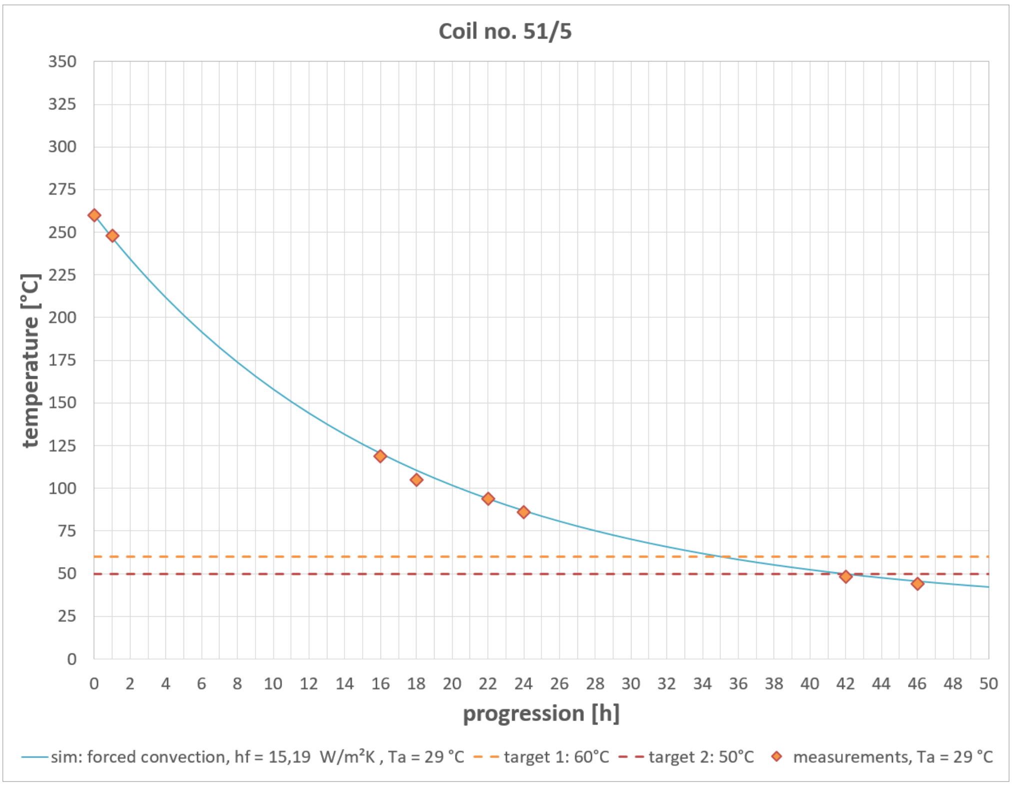

Fig. 5-6 Cooling curve of coil No. 51/5

6. CONCLUSION

In this PhD thesis, the thermal behaviour of aluminium coils was investigated with the aim of finding a cooling method for the cylinders after hot rolling that only works with regenerative cold in the buffer storage, i.e. with outdoor air. This should also lead to reducing the ecological footprint of aluminium production by avoiding active cooling with refrigeration machines. This was to be achieved on the one hand by the regenerative cooling method, and on the other hand by reducing the size of the buffer warehouse for the intermediate storage of the coils. The following steps were taken to achieve the aim:

(1) A thermal analytical model of the metal cylinders was created for this purpose. The advantage of the analytical model is the fast calculation of the simulation under given conditions in contrast to a numerical analysis according to the finite element method with a transient state calculation of the cooling process. For the model, the hollow cylinder was simplified as a cuboid at the outer dimensions. The inner tube of the coil was also considered as such in the model.

(2) On the basis of the first even simpler simulations, in which constant heat transfer coefficients from the literature were calculated in advance for both free and forced convection, the air volumes and design of the ventilation system were determined. With the parameters obtained in this way, the ventilation system was designed and implemented in a high-bay warehouse in China.

(3) Then, the expected cooling curves were simulated with the thermal model of the aluminium drums described above. To verify this analytical simulation model, measurements were then carried out on site in the same high-bay warehouse in China.

The measurements have fully confirmed the approximations in the model. As a result, a simulation tool for aluminium coils is now available, which makes it possible to calculate the cooling with a sufficient accuracy and thus determine the parameters of cooling with outside air. Thus, the metal cylinders can be cooled without rearrangement in the storage area with low energy consumption and therefore CO_2 output in the cooling of the aluminium drums.

The results show that just waiting for the metal drums to cool down on their own by placing them in a space with outdoor temperature takes over 100 h, which is too long. For the space inside the high-bay warehouse, this even takes over more than 160 h.

The data obtained in this thesis shows that a system that makes economic and ecological sense can be installed in a high-bay warehouse using comparatively simple means. The system consists mainly of fans, air ducts and exhaust grids.

The application reduces the power consumption by the factor of 16. With an electricity mix of around 550 grams of CO_2 per kWh, this means a saving of 136 kg CO_2 per aluminium coil. The benchmark for a 20 t aluminium cylinder would be 6.8 kg CO_2 savings per metric ton. Worldwide, this system could eliminate about 200,000 t of CO_2 output per year, without taking into consideration the CO_2 savings from reduced construction efforts for smaller warehouses. While this may only be a small portion of the total CO_2 output of aluminium production, installing this type of cooling system still makes ecological and economic sense.

The limitations of this thesis are clear: there were only a small number of test objects available. It is very difficult to find 20 t test objects just for experimental purposes and be able to access them within a fully automated storage facility. Additionally, the test coils did not reach the maximum dimensions that were stated in the initial requirements. Finally, the influence of fluctuations in outdoor temperature was neglected by using an average value.

This PhD study provides a new possibility for reducing the ecological footprint of aluminium production and saving money with an economically feasible system. Further research could optimize the ventilation system and make the airflow even more efficient. With a worldwide production of over 70 million metric tons per year (2023 forecast) [1] and an increasing share of over 40 % in the form of rolled metal, this should be feasible.

In addition, the developed analytical model, when implemented in the control system of the storage facility, can predict the temperature of every coil in storage with or without forced convection and without measuring the metal drums itself but only the air temperatures.

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LIST OF FIGURES

ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
ANO	anodizing
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	ASTM International (former: American Society for Testing and Materials)
CCC	controlled cooling of coils
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
EXP	experimental data
GWP	Global Warming Potential
HSC	hollow solid cylinder

HVAC	Heating, Ventilation, Air Conditioning
ISO	International Organization for Standardization
ODP	Ozone Depletion Potential
R	Refrigerant
TCC	thin-walled, concentric cylinders

CHEMICAL FORMULAE

Al	aluminium
Al_2O_3	aluminium oxide (alumina)
$Al(OH)_3$	aluminium hydroxide
C	carbon
CO_2	carbon dioxide
Cr	chrome
Fe_2O_3	iron oxide
H_2O	water
Mo	molybdenum
Na_2O	natrium oxide
Nb	niobium
Ni	nickel
NH_3	ammonium
SiO_2	silicon dioxide (silica)
O_2	oxygen
TiO_2	titanium dioxide
V	vanadium

SYMBOLS

A	area
A_i	inner tube area
A_j	jacket area
A_l	lateral area
$A_{\Sigma r}$	total area for radiation
$A_{\Sigma c}$	total area for free convection
$A_{\Sigma f}$	total area for forced convection
α, h	heat transfer coefficient
C	capacity
c	specific heat capacity
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
c_{Al}	specific heat capacity of aluminium
d	working days per year
D_a	outer diameter
D_i	inner diameter
ε	emissivity
F	acceleration
F_x	acceleration component in x direction
F_y	acceleration component in y direction
F_z	acceleration component in z direction
g	gravitational acceleration
Gr	Grashof number
H	enthalpy
H_{air}	enthalpy of air
h_c	heat transfer coefficient for free convection

$h_{f(1)}$	heat transfer coefficient for forced convection, case (1)
$h_{f(2)}$	heat transfer coefficient for forced convection, case (2)
$h_{f(3)}$	heat transfer coefficient for forced convection, case (3)
k	thermal conductivity
L	length
L_c	characteristic length of flow
m	mass
m_{coil}	mass of coil
μ	dynamic viscosity
n	number
Nu	Nusselt number
Nu_c	Nusselt number for free convection
Nu_f	Nusselt number for forced convection
$Nu_{f(1)}$	Nusselt number for forced convection, case (1)
$Nu_{f(2)}$	Nusselt number for forced convection, case (2)
$Nu_{f(3)}$	Nusselt number for forced convection, case (3)
π	number pi
p	pressure
Pr	Prandtl number
Q	heat
Q_{air}	air volume coil
Q_{coil}	heat content of coil
$\dot{Q}$	heat flow
$\dot{Q}_a$	airflow jacket outlet
$\dot{Q}_c$	heat transfer by convection
$\dot{Q}_r$	heat transfer by radiation
$\dot{Q}_z$	airflow centre outlet

ρ	density of fluid
Ra	Rayleigh number
Re	Reynolds number
σ	Stephan-Boltzman constant
S	entropy
T	absolute temperature
T_a	absolute ambient temperature
T_{coil}	absolute temperature surface of coil
T_s	absolute surface temperature
t	time
t_T	target time
τ	time constant
U	internal energy
V	volume
v	velocity
v_x	velocity component in x direction
v_y	velocity component in y direction
v_z	velocity component in z direction
W	work
ξ	friction coefficient of the smooth tube
υ	kinematic viscosity

PUBLICATIONS, POSTERS AND PRESENTATIONS

Publications in the context of this doctoral work

1. Sedlacek, D., Hausnerova, B.: Cooling Aluminium Coils by Outdoor Air. Journal Manufacturing Technology (ISSN 1213-2489) – Accepted paper 2019
2. Sedlacek, D., Hausnerova, B., Lengálová, A.: Cooling of Aluminium Coils: Numerical Simulation of Airflow for Ventilation System Design, IRF2020 – Accepted paper 2020

Conference presentations

1. Conference Aluminium and Non-Ferrous Metals 2019, October 22nd - 25th 2019 in Hrotovice, CZ
2. 7th International Conference INTEGRITY-RELIABILITY-FAILURE In Automotive, Locomotive, Aerospace, Civil Engineering and Biomechanics, September 6th – 10th 2020 in Funchal, PT, only virtual due to cancellation of the conference because of the Corona pandemic

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Cooling of Aluminium Coils by Forced Ventilation with Outdoor Air

Chlazení hliníkových cívek nucenou ventilací venkovním vzduchem

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