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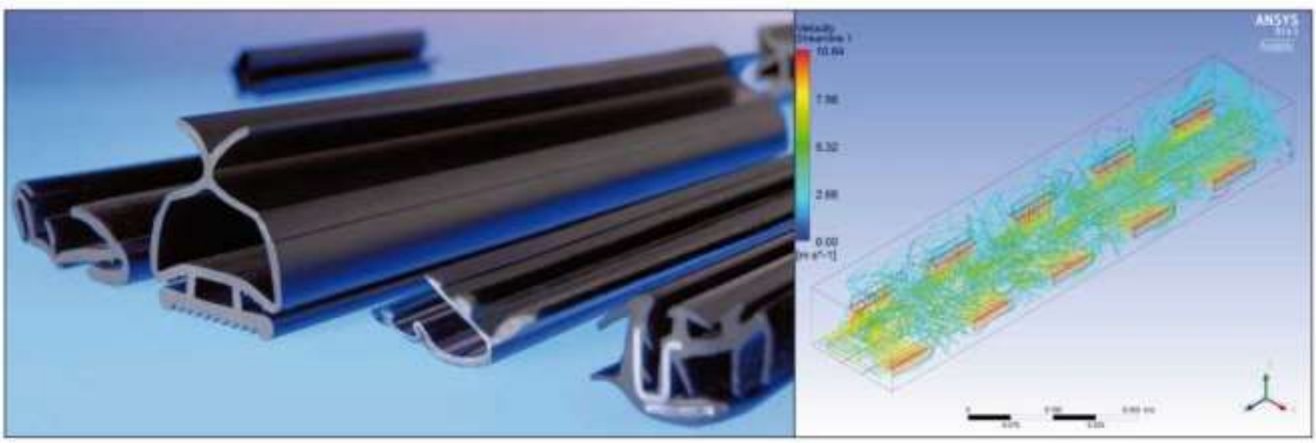
Effects of operating parameters on hot air vulcanisation

Holistic energy concept for hot air vulcanisation using innovative air flow and heat transfer



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Effects of operating parameters on hot air vulcanisation

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The hot air vulcanisation belongs to the class of pressure-less continuous curing processes and counts among the oldest procedures as well.
The heat transfer to the extrudate - necessary for the vulcanisation - is effected by hot air. In addition to the air temperature the flow velocity and the turbulence of the flow have significant influence on the temperature profile in the extrudate. An indication for the efficiency of the energy input is the heat transfer coefficient of the air depending on the flow behaviour (laminar or turbulent), the flow velocity, the temperature as well as the channel geometry being passed through. The effects of operating parameters on the heat transfer coefficient in the hot air vulcanisation will be presented and discussed.

1 Introduction

Hot air vulcanisation belongs to the class of pressure-less continuous vulcanisation processes and is also one of the oldest processes [1 - 3]. The heat necessary for the vulcanisation is transferred to the extrudate by hot air that is applied to the channel at either one or both end(s), depending on the system, with a specific flow velocity.
The leakage losses occurring there can be avoided by means of certain optimisations according to [4].

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The extrudate is continuously transported through the system by fabric belts or roller conveyors; the speed of the extrudate is defined by the upstream extrusion process.

During this process, along with the air temperature, the flow velocity and the turbulence in the flow have a significant effect on the temperature profile inside the profile [1, 2, 5]. A measure for the efficiency of the application of the energy is the coefficient of heat transfer α of air as a function of the type of flow (laminar or turbulent), the flow velocity, the temperature and the geometry through which the flow passes. In the following the effects of operating parameters on the coefficient of heat transfer in hot air vulcanisation are presented and discussed. However, the material-related side of vulcanisation is not addressed here, instead the process-related variables are addressed.

2 Basics

2.1 Laminar and turbulent flow

The air flows existing in a hot air vulcanisation channel can in principle be classified as laminar or turbulent **(Fig. 1)**. A laminar flow does not have turbulence or transverse flows and is also called a layered flow. The flow variables are mostly constant over time such that it is then also possible to talk of a steady-state flow. On the other hand there are significant fluctuations in the flow variables in a turbulent flow. This situation causes a momentum transverse to the direction of flow. The state of the flow is characterised by apparently random turbulence as a result of which there is an additional energy exchange. The heat transfer is therefore better with a turbulent flow.

A measure for the type of flow is the so-called Reynolds number. It is defined as the product of the flow velocity and the hydraulic diameter divided by the kinematic viscosity of the medium **(Equation 1):**

$$Re = \frac{v \cdot d_h}{\nu(T)} \qquad (1)$$

The kinematic viscosity ν is temperature and pressure-dependent and results from the density-related dynamic viscosity η. The hydraulic diameter d_h is defined as a function of the area and the periphery of any cross-section and corresponds approximately to a circular diameter with similar pressure losses, given the same pipe length and flow velocity **(Equation 2):**

$$d_h = \frac{4 \cdot A}{U} \qquad (2)$$

The transition between laminar and turbulent flow is defined by the critical Reynolds number and the following applies [6]:

Laminar flow:	Re < 2 300
Laminar/turbulent flow:	2 300 < Re < 10 000
Turbulent flow:	Re > 10 000

In the laminar region the flow is damped by the viscous forces. After a transition area, the flow becomes completely turbulent and is dominated by the inertial forces.

The advantage of a turbulent flow is the increased momentum, heat and material transport. Vortices are produced in the turbulence that generate dissipative heat and increase the transport in the shear and main flow direction. In addition, with a turbulent flow only a thin boundary layer needs to be overcome by means of thermal conduction, while with a laminar flow the flow lines are in parallel and then heating only occurs by thermal conduction.

2.2 Possibilities for heat transfer

Heat can be transferred by thermal conduction, by forced or natural convection, as well as by radiation.

Thermal conduction is the transport of energy as a result of atomic and molecular interactions due to a temperature gradient and only occurs in solids or fluids at rest. The flow of heat here is dependent on the temperature gradient and the material parameter λ (thermal conductivity), which is a function of the temperature and pressure. Thermal conduction is expressed using Fourier's law **(Equation 3)** [6]:

$$\dot{q} = -\lambda \cdot \nabla T \qquad (3)$$

Heat transfer due to convection is an interaction of thermal conduction and energy transport due to the flowing fluid, where the heat transfer is dominated by the flow and supported by the thermal conduction. Crucial for heat transfer by convection is the coefficient of heat transfer α.

For forced convection this coefficient is dependent on the thermal conductivity, the Nusselt number and the hydraulic diameter **(Equation 4):**

$$\alpha = \frac{Nu \cdot \lambda}{d_h} \qquad (4)$$

The dimensionless Nusselt number (Nu) defines the ratio of the total heat flow in relation to the heat flow due to thermal conduction. The calculation of the Nusselt number is dependent on the type of flow and the nature of the convection, i.e. whether the convection is forced or natural. For forced convection, which is in principle present during hot air vulcanisation, the Nusselt number is dependent on the Reynolds number and the Prandtl number.

In addition, a differentiation is made between a laminar and turbulent flow, as well as between an initial thermal flow and a fully formed flow. By visualising the flows during experimental studies in a hot air vulcanisation channel, it was possible to show that there is always a turbulent flow in the channel.

The flow is always considered fully formed, because this is a continuous, steady-state process. Based on these considerations, the following Nusselt function is used **(Equation 5)** [6]:

$$Nu = \frac{\left(\frac{\xi}{8}\right) \cdot Re \cdot Pr}{1 + 12{,}7 \cdot \sqrt{\frac{\xi}{8}} \cdot \left(Pr^{\frac{2}{3}} - 1\right)} \cdot \left[1 + \left(\frac{d_h}{l}\right)^{\frac{2}{3}}\right] \qquad (5)$$

with

$$\xi = (1{,}8 \cdot \log_{10}(Re) - 1{,}5)^{-2} \qquad (6)$$

The Prandtl number Pr is dimensionless and gives the ratio of momentum transport to the energy transport **(Equation 7):**

$$Pr = \frac{\eta \cdot c_p}{\lambda} \qquad (7)$$

To describe the local heat flow, Newton's law of cooling is then **(Equation 8)** [6]:

$$\dot{q} = \alpha \cdot \Delta T \qquad (8)$$

A further possibility for heat transfer is thermal radiation - energy transport by electromagnetic rays that do not require a material carrier. However, the disadvantage is the need for high temperatures, which can result in thermal damage to the vulcanisate. Thermal radiation is described as a function of the Stefan-Boltzmann constant σ_S as follows **(Equation 9)** [6]:

$$\dot{q}_s = E_s = \sigma_s \cdot \varepsilon \cdot T^4 \qquad (9)$$

However, heat transfer by convection is dominant during hot air vulcanisation.

3 Influence of operating parameters

Based on the preliminary theoretical considerations, the effects of operating parameters on hot air vulcanisation will now be indicated to derive possible means of improvement. During hot air vulcanisation, the energy is applied to the extrudate to be vulcanised by convective heat transfer from air to the rubber. It is therefore of immense importance that a high coefficient of heat transfer is achieved to ensure efficient, quick cross-linking of the rubber.

In hot air vulcanisation the coefficient of heat transfer α depends on the one hand on the temperature-dependent physical characteristics of the air (thermal conductivity λ, dynamic viscosity η, specific heat capacity c_p and kinematic viscosity ν), and on the other hand on the channel geometry (hydraulic diameter d_h) as well as the flow velocity v of the air. The qualitative effects on the coefficient of heat transfer are shown in **Figure 2**.

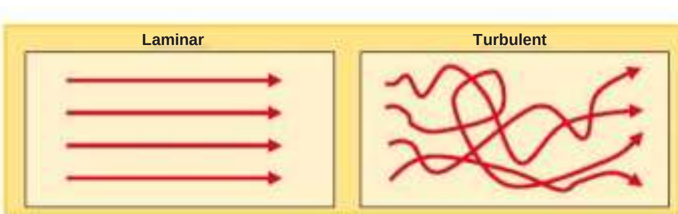


Fig. 1: Laminar and turbulent flow

From **Equation 4** it can be seen that the coefficient of heat transfer increases significantly with a reducing hot air channel diameter. This effect is not linear, because the hydraulic diameter also affects the Reynolds number and therefore also the Nusselt number (cf. **Equation 1** and **5**). The hydraulic diameter can, however, not be chosen arbitrarily small without further consideration, because the pressure loss in the channel to be overcome by a hot air fan will then continue to increase. For this reason the minimum diameter is defined by the performance of the fan.

The air temperature has a negative effect on the coefficient of heat transfer. The higher the air temperature is, the lower the coefficient of heat transfer is, where this effect is to be considered more minor. Nevertheless, an increase in the air temperature results in significantly faster vulcanisation, because along with the coefficient of heat transfer the absolute temperature of the air is of crucial importance for the temperature profile in the extrudate, as is shown in the following.

Furthermore, the coefficient of heat transfer increases almost linearly with increasing air velocity. However, there are also limits to the effectiveness of an increase in the air velocity; these limits are explained in the following section.

Because the coefficient of heat transfer α does not provide any information on how quickly a part is heated, the dimensionless Fourier and Biot numbers must be used for this purpose. Using these numbers it is possible to calculate the time after which a stipulated core temperature is achieved in an extrudate to be vulcanised. This time can be approximately equated to the vulcanisation time and using this time it is possible to make qualitative statements on the effects on the vulcanisation time.

The numbers stated above include a few material parameters on the material to be heated. The Fourier number is defined as follows **(Equation 10):**

$$Fo = \frac{a_{Kautschuk}}{\left(\frac{d_{Vulkanisat}}{2}\right)^2} \cdot t = \frac{\lambda_{Kautschuk}}{\rho_{Kautschuk} \cdot c_{p,Kautschuk} \left(\frac{d_{Vulkanisat}}{2}\right)^2} \cdot t \qquad (10)$$

Here t is the heating time (or vulcanisation time), λ the thermal conductivity, ρ the density, c_p the specific heat capacity and d the ideal thickness of the vulcanisate. Because the material data are known as a rule, it is only necessary to calculate the Fourier number Fo to determine the heating time. This is given by the relationship with the dimensionless temperature Θ **(Equation 11):**

$$\Theta = \sum_{i=1}^{\infty} \left(\frac{2 \cdot \sin(m_i)}{m_i + \sin(m_i) \cdot \cos(m_i)} \cdot \cos\left(m_i \cdot \frac{x}{d_{Vulkanisat}}\right) \cdot e^{-m_i^2 \cdot Fo} \right) \qquad (11)$$

The dimensionless temperature Θ is in turn calculated from the required temperature in the middle of the vulcanisate as well as the hot air temperature and the extrudate temperature after leaving the extruder **(Equation 12):**

$$\Theta = \frac{T_{mitte,soll} - T_{Luft}}{T_0 - T_{Luft}} \qquad (12)$$

The variable x in **Equation 11** is a moving coordinate that makes it possible to determine the dimensionless temperature at various points in the part. Because in this consideration the coordinate system is in the middle of the part in which the required temperature is to be reached, this moving coordinate goes to zero. To further simplify the equation, the first element in the summation [6] is sufficient for an adequately accurate calculation.

Fig. 2: Coefficient of heat transfer as a function of air temperature, hydraulic diameter and flow velocity

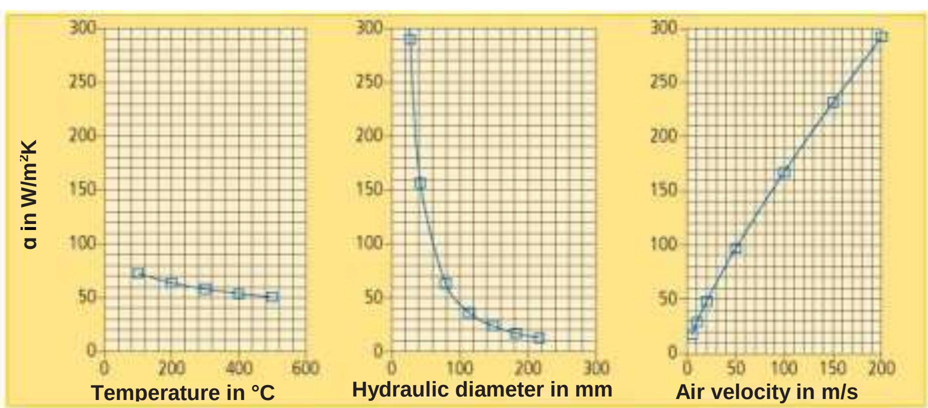
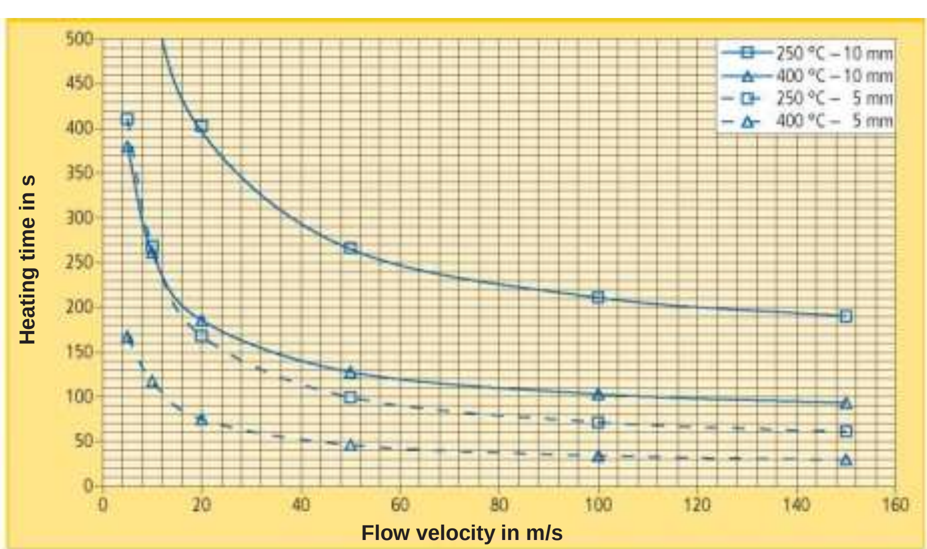


Fig. 3: Heating time as a function of air velocity/temperature and extrudate diameter



As such the Fourier number can be calculated as follows **(Equation 13):**

$$Fo = \frac{-\ln\left(\frac{\Theta \cdot (m + \sin(m) \cdot \cos(m))}{2 \cdot \sin(m)}\right)}{m^2} \quad 13$$

The parameter m can be calculated iteratively with the aid of the Biot number Bi **(Equation 14):**

$$m = \arctan\left(\frac{Bi}{m}\right) \quad 14$$

The Biot number is the ratio between the internal resistance to thermal conduction of the rubber and the external resistance to heat transfer of the flowing air and can be calculated as follows **(Equation 15):**

$$Bi = \frac{\alpha_{Luft} \cdot \frac{d_{Vulkanisat}}{2}}{\lambda_{Kautschuk}} \quad 15$$

Therefore the coefficient of heat transfer α of the hot air is taken into account in the Biot number and in this way also flows into the calculation of the heating time.

The material parameters as a function of the temperature required for the calculation of the heating or vulcanisation time and the geometry of the channel are given in **Table 1**.

With the aid of the Fourier number and the Biot number, the heating time can be calculated as a function of the flow velocity for different air temperatures and extrudate sizes **(Fig. 3).**

An idealised cuboid with a square cross-section was chosen for the extrudate geometry.

In principle it can be seen that doubling the extrudate or product thickness increases the heating time by a factor of 2.5. Furthermore, the air temperature also has an immense effect on the heating time. Even though the coefficient of heat transfer is lower at a higher temperature, as expected a high temperature improves the heating time. However, the heating time cannot be arbitrarily reduced by higher temperatures, because otherwise the material will be damaged thermally. The flow velocity of the air has, however, the greatest effect. In particular, at low velocities an increase in the velocity has a very significant effect. From speeds from 80 to 100 m/s an almost constant value is achieved from which a further increase in the air velocity has no further effect. Here the process is no longer dominated by the heat transfer between air and vulcanisate, instead it is dominated by the thermal conduction in the rubber. Because in common hot air vulcanisation machines the air velocity is 10 to 15 m/s, here there is major potential for increasing the efficiency of hot air vulcanisation machines.

By increasing the flow velocity, either the heating time can be reduced or, with the same heating time, the air temperature required reduced.

Along with a reduction in the heating time, it is also possible to shorten the cross-linking section.
This aspect is particularly relevant for mixtures in which cross-linking is critical if machine length is limited.

4 Summary

The application of energy to the extrudate to be vulcanised in hot air vulcanisation is dominated by convective heat transfer from air to the rubber. The thermodynamic relationships show that the coefficient of heat transfer is dependent on the air temperature, the hydraulic diameter and the air velocity. As such by reducing the channel cross-section, the coefficient of heat transfer can be increased in two ways and improved. On the one hand the hydraulic diameter of the channel is reduced and on the other hand the air velocity significantly increased, given a constant volumetric air flow rate. However, there are limits from which a further increase in the heat transfer becomes inefficient. These limits are reached if the heating time is no longer dominated by the heat transfer from the air to the vulcanisate, but instead by the thermal conduction in the actual vulcanisate.

Tab 1: Parameters for the calculation of the heating time as a function of the air velocity

Temperatures		Geometry of the channel	
Extrudate temperature T_0	100 °C	Length l	12 m
Required temperature T_{Req}	200 °C	Width b	0.2 m
Θ for T_{Air} = 250 °C	0.33	Height h	0.1 m
Θ for T_{Air} = 400 °C	0.67	Hydraulic diameter d_h	0.13 m
Material data for air for 250 °C		**Material data for air for 400 °C**	
Thermal conductivity λ	0.041382 W/(m·K)	Thermal conductivity λ	0.05024 W/(m·K)
Kin. viscosity ν	$4.203 \cdot 10^{-5}$ m²/s	Kin. viscosity ν	$6.436 \cdot 10^{-5}$ m²/s
Prandtl number Pr	0.6993	Prandtl number Pr	0.7081
Material data for rubber			
Thermal conductivity λ	0.2 W/(m·K)		
Density ρ	1 000 kg/m³		
Heat capacity c_p	2 000 J/(kg·K)		

5 Literature

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