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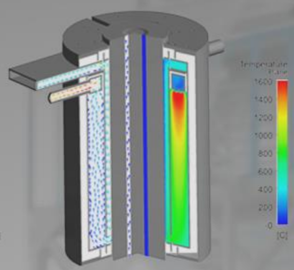
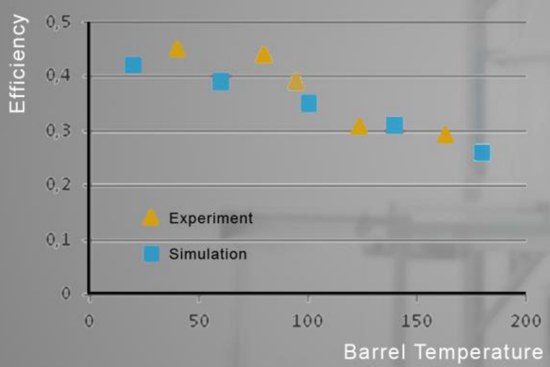
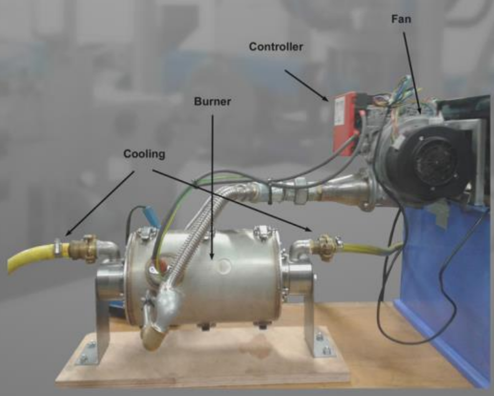
Research

KOENST PART 1

SIA Raak International: Renewable energy-efficient plastics production technologies







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Preface

In the coming years a great challenge for the plastic processing industry will be to meet the targets for energy and carbon dioxide reduction. These targets have been agreed at national level between the Dutch government and industry in a covenant, the MJA-3. The project ‘Sustainable production in the plastic industry’, which was executed by Windesheim University of Applied Sciences in 2011, heightened the awareness within the plastic processing industry of the possibilities and necessity of energy efficiency. In addition, the need for new innovative solutions for energy reduction was clearly established. In line with these developments, a new project was proposed with a focus on the development of innovative solutions.

This new project is called: ‘Renewable energy-efficient plastics production technology for international and medium-sized enterprises’. The project was funded by the Dutch government through the Innovation Alliance Foundation (Stichting Innovatie Alliantie (SIA)) within its ‘Raak International’ program. The aim of this program is to create possibilities for practical innovations through cooperation and knowledge exchange between professionals in, for example, knowledge centres and medium-sized enterprises, both regional and foreign-based.

The cooperation on the project with the University of Duisburg was formed within the Institute of Product Engineering (IPE). The project has three areas of focus: energy optimization of production processes, use of alternative and sustainable energy sources, and re-use and storage of residual heat. During the past years, the institutes of both universities have built scientific knowledge and, by applying this in the above-mentioned fields, a strong consortium with a network of medium-sized enterprises, like SHS, WEMA, 3Force, Dion, BPI-Indupac, Sphere, Dumocom, EARS and FHT.

In this report the results in all three fields of investigation are presented in two different documents. The preface, summary, introduction, dissemination and acknowledgement are incorporated in each document almost unchanged. Part one will cover the use of alternative and sustainable energy sources and part two will cover the other two areas.

A complementary outcome of this project has been the development of a new course: ‘numerical analysis of flow and heat transfer’. In part one a separate chapter has, therefore, been incorporated in order to explain this technique in the applications dealt with in the project. The name of the project is ‘KOENST’, which is an amalgamation of the German and Dutch words for ‘ART’. Actually, the sustainability of energy is appreciated based on the way you look at it, just like with paintings.

Summary

Climate change has resulted in considerable attention being paid to the reduction of energy consumption in production processes. In plastics processing, in particular, a lot of energy is used for the heating and melting of granules and for the cooling and solidification of the plastic products. In order to reduce this energy usage, every company needs to formulate and implement an effective energy policy plan. In such energy policy plans the following four stages can be distinguished: awareness, management, optimization and innovation. In an earlier research project, conducted by Windesheim University of Applied Sciences, attention was already paid to energy management and energy optimization. In this study, the focus is on energy innovation. At this stage in developments, considerable process knowledge is required and large investments in time and resources are expected.

In chapter two a research method is presented, through which - by means of numerical simulations of the flow and heat transfer - energetic processes that occur in the plastics processing can be analyzed. An advantage of this method, compared to measurements, is that a deeper and more-detailed knowledge of the processes is made possible. This advantage is demonstrated by the simulation of the heat transfer from the flue gases of a gas-fired burner to the polymer melt in the extruder of an injection molding machine. Detailed information relating to the temperatures in the burner can be obtained by this method. An understanding of the relative contribution of convection and radiation to heat transfer can also be obtained. This understanding makes it possible to further develop and optimize this burner. A disadvantage of the method is that this is based on approaches and simplifications of the actual physical processes and, therefore, validation through experimentation remains necessary.

In chapter three this numerical method is applied to determine the maximum temperatures of an existing design for a gas-fired burner. On the basis of these temperatures, the thermal stresses in the parts of the burner are analyzed and possible areas for cracking are determined. These areas match the weak spots found in the burners after a visual inspection. These burners have been in the production of large injection molding products for more than two years. Based on these findings a new burner design has been created. The different parts of the burner are designed as individual parts, which can expand independently of each other. This new design has been examined for maximum temperatures and high stress concentrations using numerical simulations. The new burner does not show high stress concentrations due to thermal expansion and does not, therefore, cause cracking. The efficiency of the burner is also determined by means of numerical simulation. This simulation shows the efficiency to be greater than 30% whereby the energy consumption is lower than electric heating. The above-mentioned numerical simulations have been validated in a functional test and in a duration test. The results of the tests were found to be broadly consistent with the simulations.

In the last chapter the dissemination of the knowledge gained is presented and plans for further research are proposed. The development of knowledge of the processes in an extruder and the rheological behavior of a fluidized bed are specific topics for follow-up investigations.

Samenvatting

Als gevolg van de klimaatverandering wordt veel aandacht besteed aan het terugdringen van het energieverbruik in productieprocessen. Met name in de kunststofverwerking wordt veel energie gebruikt voor het verwarmen c.q. smelten en het afkoelen c.q. stollen van kunststoffen. Om dit energieverbruik terug te dringen dient ieder bedrijf een gedegen energiebeleidsplan op te stellen en uit te voeren. In dergelijke energiebeleidsplannen kunnen vier verschillende stadia worden onderscheiden, te weten: bewustwording, management, optimalisatie en innovatie. In een eerder onderzoeksproject van Hogeschool Windesheim is reeds aandacht besteed aan management en optimalisatie van energievraagstukken. In dit onderzoek ligt de focus meer op energie-innovatie. Met name in dit stadium is veel proceskennis nodig en zijn grote investeringen in tijd en middelen te verwachten.

In hoofdstuk twee is een onderzoeksmethode gepresenteerd, waarmee door middel van numerieke simulaties van de stroming en de warmteoverdracht energetische processen, die optreden in de kunststofverwerking, kunnen worden geanalyseerd. Een voordeel van deze methode ten opzicht van metingen is dat een diepgaander en gedetailleerder kennis van de processen mogelijk is. Dit voordeel is gedemonstreerd aan de hand van het simuleren van de warmteoverdracht van de rookgassen van een gasgestookte brander naar de polymeersmelt in de extruder van een spuitgietmachine. Met deze methode kan gedetailleerde informatie met betrekking tot de temperaturen in de brander worden verkregen. Tevens kan inzicht worden verkregen in de relatieve bijdrage van respectievelijk convectie en straling aan de warmteoverdracht. Hiermee is het mogelijk deze brander verder te ontwikkelen en te optimaliseren. Een nadeel van de methode is dat deze gebaseerd is op benaderingen en vereenvoudigingen van de werkelijk optredende fysische processen. Derhalve blijft validatie door middel van experimenten noodzakelijk.

In hoofdstuk drie is deze numerieke methode toegepast om de maximale temperaturen van een bestaand ontwerp voor een gasgestookte brander te bepalen. Op basis van deze temperaturen zijn de thermische spanningen in de onderdelen van de brander geanalyseerd en zijn mogelijke gebieden voor scheurvorming bepaald. Deze gebieden blijken overeen te komen met de gevonden zwakke plekken van branders na een visuele inspectie. Deze branders zijn twee jaar operationeel geweest in de productie van grote spuitgietdelen. Op basis van deze bevindingen is een nieuw branderontwerp gemaakt. De verschillende onderdelen van de brander zijn ontworpen als losse delen, die onafhankelijk van elkaar kunnen uitzetten. Dit nieuwe ontwerp is met behulp van numerieke simulaties onderzocht op maximale temperaturen en hoge spanningsconcentraties. De nieuwe brander vertoont geen hoge spanningsconcentraties als gevolg van thermische uitzetting, waardoor scheurvorming voorkomen wordt. Tevens is door middel van numerieke simulatie de efficiency van de brander bepaald. Hieruit bleek de efficiency groter te zijn dan 30%, waarbij het energieverbruik lager is dan elektrische verwarming. Bovenstaande numerieke simulaties zijn gevalideerd in een functionele test en een duurproef. De resultaten van de proefnemingen bleken in grote lijnen overeen te komen met de simulaties.

Tenslotte is in het laatste hoofdstuk de disseminatie van de opgedane kennis besproken en worden voorstellen gedaan voor verder onderzoek. Met name het ontwikkelen van kennis van de reologische processen in een extruder en het gedrag van een ‘fluidized’ bed zijn onderwerpen die voor vervolgonderzoeken in aanmerking komen.

Contents

1 Introduction and motivation

Buist, J.

Energy consumption constitutes about 10% of the costs within the plastics processing industry, which is, after material and labor, the third main cost [1]. The main energy uses and costs are related to machinery and services (92%). Lighting, heating and offices are minor contributions to costs (8%) (see figure 1.1). Due to the continuing increase of energy prices and the desire to reduce greenhouse gas emissions, saving energy has become even more important. Basic techniques to reduce energy are simple and easily applied and savings of 30% or even higher have been reported. With the right focus by industries on reducing energy consumption, the goal of 30% in energy reduction in the MJA-3 covenant can be considered feasible.

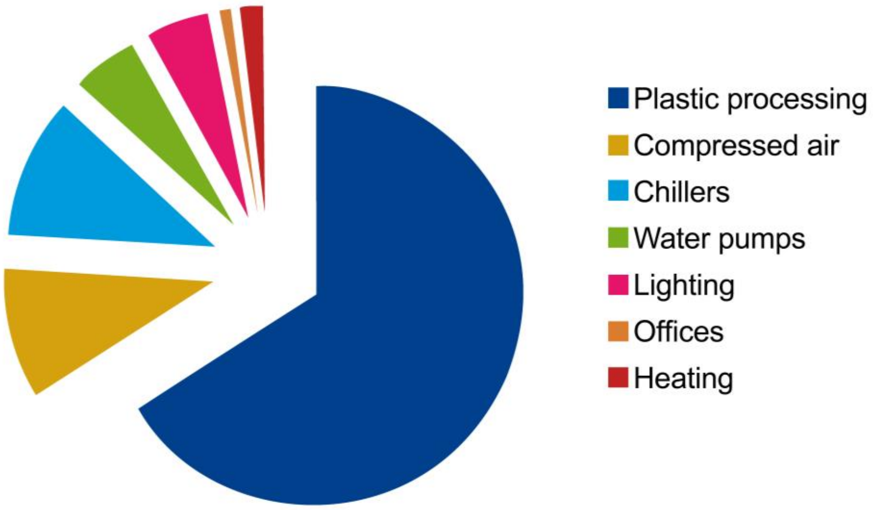


Figure 1.1: Approximate energy cost distribution for plastics processing, taken from [I] with permission from R. Kent

1.1 STAGES IN ENERGY SAVING POLICY.

Companies are obliged to develop an Energy Saving Plan (EEP) every four years and to report on progress and implementation annually. To meet these requirements several stages in energy policy can be distinguished. These are energy awareness, energy management, process optimization and process innovation and are explained in the following sections.

Energy awareness:

In the SIA project [2], which has been mentioned earlier, an energy scan (NRG Scope) has been developed in which plastic processing industries can rank themselves by comparing their energy use with similar production facilities. Based on this scan, the possibilities to reduce energy use can be mapped. This method has been applied to all of the participating industrial partners in the project. The scan focuses on the use of energy for lighting, heating, offices and transport. Advice is given with respect to, for example, automatic computer shutdown and the use of led lighting instead of light bulbs. Although these costs only represent 8% of the total energy consumption, mapping these costs is important to heightening awareness amongst personnel and building motivation for improvements in the total production process.

Energy management:

Besides the actual processing, heating and cooling of the plastics, many utilities, such as water pumps, hydraulics, chillers, compressed air and conveyer belts, use a lot of unnoticed energy. With good energy management these costs can easily be reduced, for example by switching-off the conveyer belts during stoppages of the processing machine. The implementation of variable speed drives will also contribute to energy savings in dynamic process conditions. Many more examples can be found in [1]. Timely maintenance of these utilities will also keep them in optimal condition resulting in minimized energy consumption. The energy consumption of all utilities has to be measured individually and compared to machine data sheets. Discrepancies with normal operations inform the management to take action. If these signals are not ignored, energy management successfully leads to energy savings and, therefore, more profit.

Process optimization:

The main part (66%) of the energy consumption is due to plastic processing, melting of the granules and solidification of the product. In the project mentioned earlier a process parameter effect method (PEM) has been developed [3]. This method is a practical and easy-to-use approach to gain insight into the effect process parameters have on product characteristics such as weight, dimensions, energy consumption and use of additives. Minimizing the weight of a product reduces the amount of material to be melted and, therefore, reduces energy consumption. This method has been successfully applied to injection molding, extrusion, sheet molding and blow molding. Depending on the production method, average savings in material use were found to be 2.6%, while the energy consumption could be reduced by 6.7%. Alternatively, cost savings could be achieved by reducing an additive such as dye. It was found that a reduction of 35% in added dye resulted in acceptable (good) quality products. The findings also showed that the highest energy savings were in sheet and compression molding due to the enormous amount of air needed for cooling and compression.

Process innovation:

Innovations in the production process are necessary due to rapidly changing markets and advancements by competitors. In addition, the transition to sustainable energy sources, such as biomass and geothermal heat pumps, gives rise to the development and implementation of new process equipment. For example, with geothermal heat, plastics granules can be preheated before feeding to the process machines. Solutions have to be found on how to exchange heat to the plastic granules in the daily stock. It is important that acceptable temperature levels are chosen in order to prevent the granules sticking during transportation to the machine. The plastic process industry also produces a lot of residual heat due to the cooling and solidification of the mold. Unfortunately, the cooling air can be heavily contaminated with paraffin wax, for example in the sheet molding process. These complications have to be analyzed and the effects on product quality have to be mapped or solutions for cleaning have to be found.

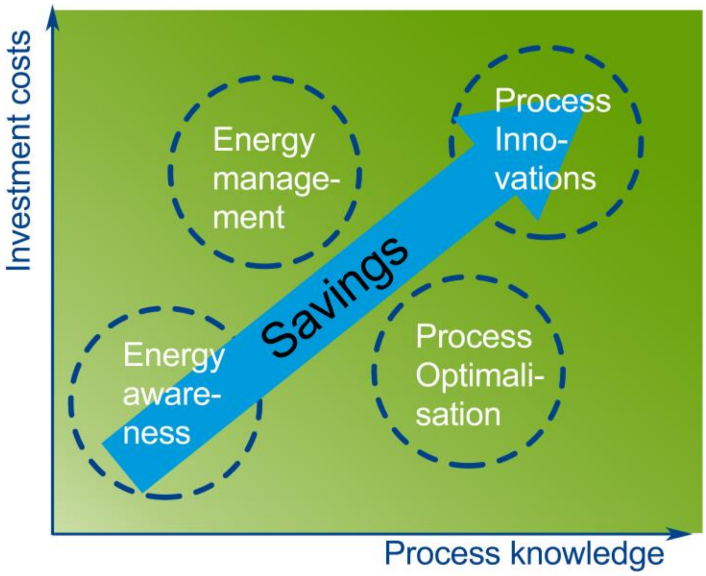


Figure 1.2: Stages in energy policy

The stages in energy policy need different levels of investment costs and knowledge of the production processes. These different levels are graphically shown in figure 1.2, where on the x-axis the process knowledge, which is needed to implement the adjustments, is plotted against the investment costs on the y-axis. The coloring of the boxes from light green to dark green indicates the potential for sustainable improvements. Savings in energy costs are indicated by the blue arrow.

The investment costs are high for process innovation as a result of the research and development costs of new processes as well as the purchasing, implementation and testing of new equipment. Alternatively, optimizing the production process by changing the settings of the machines can be done with little investment in machinery. A thorough understanding of the physics of the processes is needed. From this picture it can be concluded that to save the largest amount of energy costs a thorough knowledge of the production processes is needed.

It must be noted that these innovations cannot be achieved solely by the plastic processing industry itself. These innovations need cooperation between knowledge institutes and solution providers for utilities and equipment. By incorporating all these parties in this project, valuable initiatives can be achieved.

1.2 HISTORICAL BACKGROUND OF AN ALTERNATIVE ENERGY SOURCE.

The concepts of a heating system based on natural gas instead of electrical resistance heaters were first presented in [4], [5] and [6]. The basic idea was that the heat is directly applied to the melting process by heating the barrel by means of radiation and convection of the heat from the exhaust gasses, see figure 1.3. This principle can be implemented in many different plastics processing machines, for example injection molding machines, extruders for blow molding, etc.

The direct cost savings can be estimated by considering the cost of gas (€ 0,05/kWh) with an efficiency of the combustion process of 40% compared to the cost of electricity (€ 0,20/kWh) with an efficiency of 90%. It easily can be seen that more than 30% savings are possible in case of a gas fired heating system. But it is important to note, that these prices are influenced by national governmental politics, which makes a cost comparison indistinct and dynamical.

A reduction of CO2 can be achieved if the overall efficiency of the burner is at least as high as modern power stations for electricity production, taking also into account the losses due to transformation and transport of energy. Other reported advantages of gas heating are [4]: a more homogeneous melt, higher warm-up speeds of the melt and the possibility to include cooling of the equipment with the same geometry by blowing only cold air through the burner, see figure 1.3.

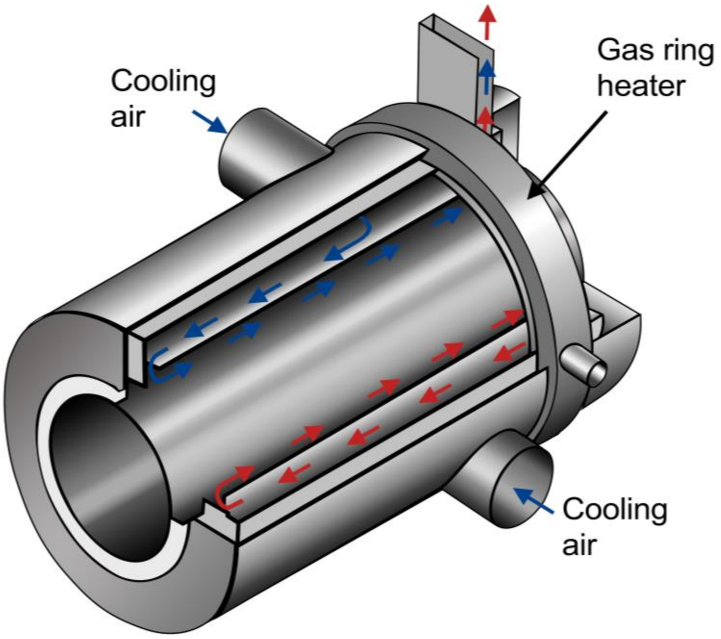


Figure 1.3: Gas fired heating

A prototype of a gas heated burner was built, tested and delivered to an injection molding company in the south of Germany about eight years ago. In order to increase the production of injection molding a gas fired system was chosen instead of electrical heating for new machines. This meant there was no need to expand their electricity supply, which is extremely costly. This prototype was successfully operated for more than two years on a daily basis. After this trial period, the system was dismantled and the construction was examined by visual inspection. In parts of the construction the onset of crack formation was found, most likely due to thermal stresses. Although these cracks never led to failure of the construction they have to be avoided to ensure a longer lifetime.

In chapter two the research methodology for investigating these challenges is presented. In the third chapter the initiative for the gas-fired burner is analyzed, redesigned and validated.

References

[1] Kent, R. (2008) Energy Management in Plastic Processing.
[2] Boks, N. and Dijk, T. van (2011) Meer producten, minder energie (duurzaam produceren in de kunststofindustrie, Windesheimreeks kennis en onderzoek.
[3] Boks, N. (2011) Procesparameter effect methode (handleiding), Windesheimreeks kennis en onderzoek.
[4] Wortberg, J. and Schroer, T. (2003) Novel Barrel Heating with Natural Gas, ANTEC event.
[5] Wortberg, J. (2010) An alternative plastification system based on natural gas, Journal of plastics technology, 6, 2.
[6] Andelt, M., Artkamp, J. and Seibert, H.D. (2004) Method and device for heating a plasticizing cylinder, European patent number EP1300233, Applicants Ruhrgas AG and Wema GmbH.

2 Research methodology

Buist, J. and Hummel, C.

To analyze flow related problems, like combustion processes and heat exchange, numerical simulation can be performed instead of carrying out costly experiments. In case of simulation there is no need for an expensive prototype and hence quick changes in the geometry can be made. Another important advantage of simulation, with respect to experiments, is to visualize the observed behavior of mass and heat flow in more detail. Also with respect to safety no special arrangements have to be made to avoid dangerous or polluted situations. On the other hand simulations are an approximation of reality which means that results have to be validated with analytical data or experimental values. Simulations for flow related problems are generally known as computational fluid dynamics (referred to as CFD). In this section an example is given of how to perform CFD simulations for a gas fired burner, which was introduced in section 1.2.

Nomenclature

u,v,w = velocity vector	m/s	x,y,z, = cartesian coordinate system	m
n = normal direction	-	t = time	s
Γ = arbitrary variable	-	Φ = arbitrary variable	-
ρ = density	kg/m^3	p = pressure	Pa
T = temperature	K (°C)	h = Enthalpy per unit mass	J/kg
ν = kinematic viscosity	m^2/s	ν_t = turbulent viscosity	Pa.s
k = turbulent kinetic energy	m^2/s^2	ε = turbulent dissipation	Pa/s^2
Pr = Prandtl number	-	Prt = turbulent Prandtl number	-
Re = Reynolds number	-	Sc = Schmidt number	-
N = amount of chemical species	-	i,p,j = chemical species	-
M_w = molecular weight	kg/kmol	μ = dynamic viscosity	Pa.s
S = general source term	kg/m^3s	Y = mass fraction	-
R = reaction source term	kg/m^3s	D = diffusion coefficient	m^2/s
S = radiation loss or gain	J/m^3s	ν_R = stoichiometric coefficient	-
λ_s = thermal conductivity of steel	W/mK	κ = thermal conductivity of flue gas	W/mK
σ = Stefan Boltzmann constant	J/sm^2K^4	ε_w = the emissivity of the wall	-
η = efficiency	%	Φ_m = mass flow	kg/s
c_w = heat capacity of water	J/kgK	H_0 = heating value	J/m^3

2.1 CONSERVATION LAWS

The numerical method, see [1] and [2], is based on solving the partial differential equations for conservation of mass, impulse and energy. These equations can be summarized by the following transport equation,

$$\frac{\partial \Phi}{\partial t}+\frac{\partial (u\Phi)}{\partial x}+\frac{\partial (v\Phi)}{\partial y}+\frac{\partial (w\Phi)}{\partial z}=\frac{\partial}{\partial x}\left[\Gamma\frac{\partial \Phi}{\partial x}\right]+\frac{\partial}{\partial y}\left[\Gamma\frac{\partial \Phi}{\partial y}\right]+\frac{\partial}{\partial z}\left[\Gamma\frac{\partial \Phi}{\partial z}\right]+S_{\Phi} \quad (1)$$

where Φ and Γ are arbitrary variables denoting different quantities for mass, impulse or energy. In the differential equation for mass conservation Φ means the density of the gasses and Γ equals zero. In the impulse balance Φ represents the velocity field, Γ represents the viscosity of the fluid and the source term S_{Φ} the pressure gradient. In the energy equation the variable Φ will be replaced by the temperature, Γ represents the viscosity divided by the Prandtl number and S_{Φ} is a source term for heat production.

In case of turbulent flow the partial differential equation is solved by using the Reynolds Averaged Navier-Stokes (RANS) solver and a suitable turbulence model has to be chosen. For example, in the (k,ε) turbulence model also the transport equations for turbulent kinetic energy, Φ = k, and turbulent dissipation, $\Phi = \varepsilon$, have to be solved. In the impulse balance the viscosity has to be added with a turbulent viscosity

$$\Gamma=\upsilon+\upsilon_T \quad (2) \qquad \Gamma=\frac{\upsilon}{P_r}+\frac{\upsilon_T}{P_{rT}} \quad (2)$$

and in the energy balance the heat transfer coefficient has been changed by adding a turbulent contribution based on the turbulent viscosity.

In this project a commercially available solver, ANSYS CFX, has been used with the shear stress transport (SST) model for turbulence. This model has been used to calculate the boundary layers with respect to heat transfer accurately.

2.2 PHYSICAL MODEL FOR COMBUSTION

Apart from these transport equations, also physical models for the combustion process and heat transfer have to be applied. In this section the concepts of all physical models, which have been used, will be shortly discussed. More information can be found in [2] and [3].

In combustion simulation the transport equation for mass has to be applied on all chemical species in the process, for example methane (CH_4), air (O_2, N_2 and H_2O) and the flue gasses (CO_2, H_2O, O_2 and N_2). It is clear, that not only the rate of change of mass in time and decrease of mass due to convection have to be balanced. Also, the increase of mass due to the reaction process has to be involved and hence diffusion of mass. The conservation of mass then reads:

$$\frac{\partial}{\partial t}(\rho Y_i)+\frac{\partial}{\partial x_j}(\rho u_j Y_i)=\frac{\partial}{\partial x_j}\left(\rho D_i \frac{\partial Y_i}{\partial x_j}\right)+R_i+S_i \quad (3)$$

Where D_i is the diffusion coefficient for all species and R_i is the reaction source term.

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial x_j}(\rho u_j h)=\frac{\partial}{\partial x_j}\left(\frac{\mu}{P_r}\frac{\partial h}{\partial x_j}+\left(\frac{1}{Sc_i}-\frac{1}{P_r}\right)\sum_{i=1}^{N} h_i \frac{\partial Y_i}{\partial x_j}\right)+\frac{\partial p}{\partial t}+S_{rad} \quad (4)$$

To calculate the different source terms R_i for each species several combustion models can be applied. In this project the eddy dissipation model has been used, which is available in CFX.

The eddy dissipation model is a model for calculation of the reaction source term used in the mass fraction transport equation. The eddy dissipation model is based on the turbulent mixing rate. The eddy dissipation model assumes that chemical reactions occur much faster than turbulence can mix the reactants and heat, therefore making turbulence the limiting force. This is very plausible with the combustion of turbulent premixed gases. The eddy dissipation model uses the equations shown below to calculate the reaction source term.

$$R_{i,r} = v'_{r,R} \cdot M_{w,r} \cdot A \cdot \rho \cdot \frac{\varepsilon}{k} \cdot \min_{r} \left(\frac{Y_r}{v'_{r,R} \cdot M_{w,r}} \right) \quad (5)$$

$$R_{i,r} = v'_{r,R} \cdot M_{w,r} \cdot A \cdot B \cdot \rho \cdot \frac{\varepsilon}{k} \cdot \frac{\sum_p Y_p}{\sum_{p=0}^{N} v''_{p,R} \cdot M_{w,p}} \quad (6)$$

The rate of production of reactant r and product p in reaction R, is given by the smallest result of the two equations above. The upper equation is based on the mass fraction of reactants and the lower equation is based on the mass fraction of products.

2.3 APPLICATION, AN ALTERNATIVE HEATING

In this section the geometry set-up, the numerical model and the analysis of the results for the gas fired burner will be presented. The objective of the 'initial' simulations for the gas fired burner was to judge the efficiencies of an axial burner with respect to a radial burner. Also the difference between countercurrent flow or concurrent flow, which means the direction of the flue gases with respect to the granulate flow, has been analyzed. The third question to be answered is: Will heat transfer be dominated by radiation or by convection for this type of burner?

2.3.1 GEOMETRY

The principles of the geometry of the burner are shown in chapter 1, figure 1.3. In figure 2.1 the radiation plate is highlighted in red. Behind the plate, fins are placed to guide the flow in axial direction. The numerical domains are depicted in different colors in figure 2.2. The burner consists of different parts as the combustion chamber (red), the gas inlet (green), the burner plate (yellow, for a detailed picture see figure 2.3), the radiation plate and the housing (black). The blue area and grey area are respectively the mold and the barrel of the injection molding machine. The function of all these domains will be discussed briefly.

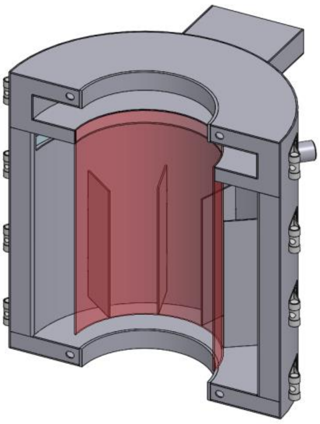


Figure 2.1: Geometry

The mold:
In this domain, the blue area in figure 2.2, the melting granules are represented by either water or thermal oil. The reason for this simplification is that in the functional test water has been used and for the duration test thermal oil. Further, the screw has been neglected. The direction of the flow inside the barrel can be in concurrent or countercurrent direction of the flue gasses in the area between the radiation plate and the barrel.

Barrel:
The barrel, the grey area in figure 2.2, consists of thick walled steel to withstand the high pressures in the mold. In the steel only conduction of heat has been modeled.

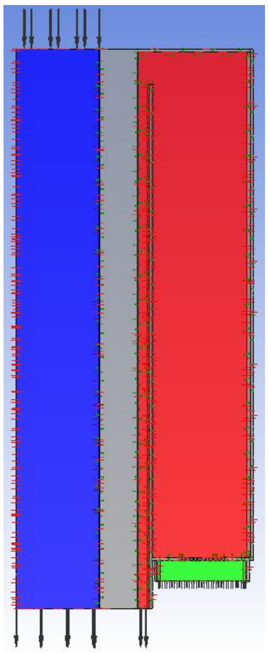


Figure 2.2: Numerical domains

Radiation plate:
The radiation plate prevents a direct contact of the flame with the barrel of the injection molding machine. Despite the high flame temperatures the barrel has to remain dimensional stable with respect to the rotation of the screw. On the other hand the flue gasses will heat up the radiation plate above say 800 K, such that this plate will radiate heat towards the barrel of the machine.

Combustion chamber:
The combustion chamber has be constructed in such a way that the flame has enough length to avoid the production of carbonmonoxide (CO). This means, that the distance between the burner plate and the opposite wall has to be long enough (as a rule of thumb, this distance has to be larger than 4 cm).

Housing:
The housing of the burner will be modelled as an adiabatic wall, since in practice the burner has been insulated to prevent leakage of heat.

Gas inlet:
In the gas inlet the mixture of gasses will be distributed in such a way that a homogeneous flame occurs above the burner plate. This inlet can be positioned perpendicular to the axis of the screw in the barrel, as shown in figure 2.3, or along the axis of the barrel. The first is called an axial burner and the latter a radial burner depending on the direction of the flame.

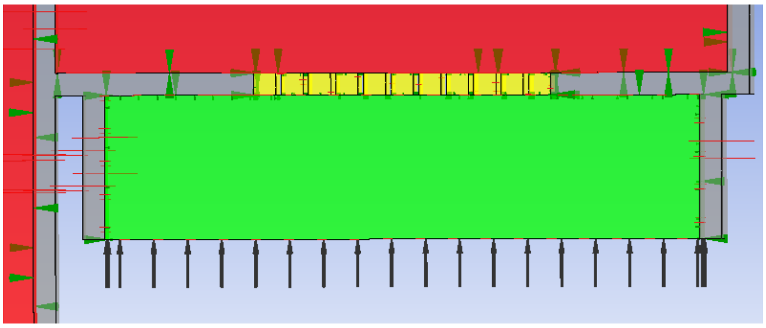


Figure 2.3: Gas inlet and burner plate

Burner plate:
The burner plate is constructed of a perforated plate with knitted burner material on top of it. This knitted material protects the perforated plate against the high flame temperature. In the burner a pre-mixed mixture of methane with an excess of air has been used. The combustion is ignited by applying a high temperature within the combustion chamber. In practice this high temperature will be delivered by an ignition pen. But, the combustion in the numerical model is on the turbulent mixing rate, which means that the gases already will react in the gas inlet. To avoid this only the air will be supplied to the inlet, since this is the largest volume of gases. To inject the fuel, the holes in the perforated plate and the knitted material are modelled as a porous medium with a source term for the fuel.

2.3.2 MODEL SET-UP

In this section the simplifications for the geometry, the grids for the numerical simulation, the boundary conditions and the physical properties for the calculation will be discussed briefly. Only the most important phenomena will be mentioned, like numerical grid, combustion model and radiation model. For a detailed description of the process see the internal report [a].

In order to reach the objectives of this investigation, the difference between a axial burner or radial burner with respect to efficiency, it is not necessary to calculate the total burner. Therefore the geometry has been simplified by taking only a slice of the burner with symmetry planes on the walls for the circumferential symmetry, see figure 2.4.

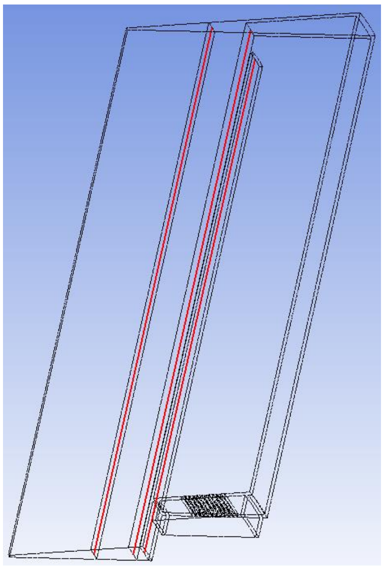


Figure 2.4: A slice of the burner

With respect to the numerical grid it is important to note that the resolution near the surface of the barrel in the flue gas domain and the radiation plate is fine enough to represent the thermal boundary layer. Therefore on both sides an inflation layer of five layers has been applied with at least five tetrahedral cells in between.

For the combustion process the eddy dissipation model has been used with coefficient A equal to 4 and the coefficient B equal to 0.5 in the equations (5) and (6). These coefficients are commonly used for gas phase combustion, see [4]. The material properties have been specified using the two-step reaction model, see [5], which is commonly used for methane-air mixtures. A complete combustion has been obtained by using an oxygen-fuel ratio of 1.1 to avoid H2 oxidation, see [6].

The thermal radiation from the combustion is calculated by the Monte Carlo method with a number of histories of 10.000 to reduce computation time. The spectral model is gray, because there are no highly reflective walls in the geometry. The wall of the barrel is specified as opaque, which means that all radiation is reflected at the wall or absorbed at the surface specified by the magnitude of the emissivity factor. In this case the emissivity is specified as 0.5, which is an average value of all different conditions of a steel plate, see [7]. The absorption coefficient of the flue gasses is specified as 1 m-1.

2.3.3 RESULTS AND ANALYSIS

In this section the flow field, the temperature field, the temperature profiles on different walls, the heat fluxes and the efficiency of the burner will be shown. The dimensions of the burner are based on an injection molding machine with a barrel diameter of 149 mm.

Flow field:

The flow field for the radial burner, figure 2.5, as well as the axial burner, figure 2.6, are given in contour plots and vector plot. The difference in flow behavior can be seen clearly.

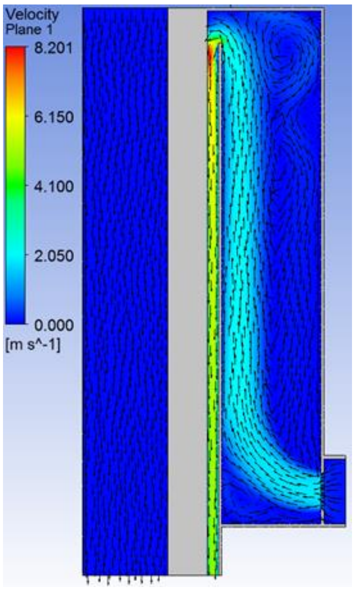


Figure 2.5: velocity radial burner

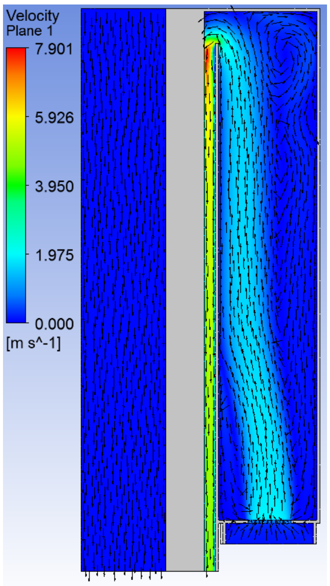


Figure 2.6: velocity axial burner

In case of the radial burner the flow has to turn upwards resulting in a recirculation zone at the bottom of the combustion chamber. Also strong recirculation zones are observed at the top of the burner. In the axial burner the recirculation at the bottom is non-existing and the recirculation at the top is less distinct. As a result, the maximum velocity of the flue gasses between the radiation plate and the barrel of the machine is slightly lower with respect to the radial burner.

Temperature field:

The temperature fields are given in figure 2.7 and 2.8 respectively for the radial burner and the axial burner. In case of the radial burner the flame is pointing towards the radiation plate and bent to the top. Therefore the hot zone of the flame in the radial burner is more attached to the radiation plate with respect to the flame in the axial burner, which might cause a higher temperature of the radiation plate and hence a higher radiative contribution to the heat flux. Analysis of the temperature profiles on the radiation plate shows, that differences in temperature hardly can be found.

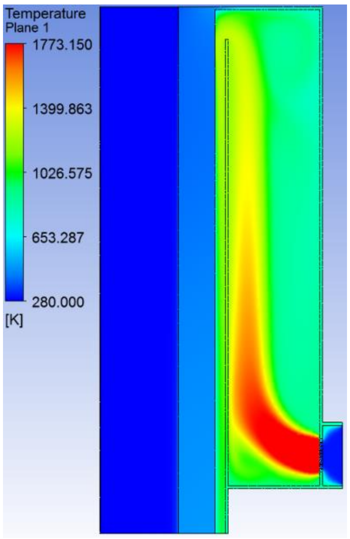


Figure 2.7: temperature radial burner

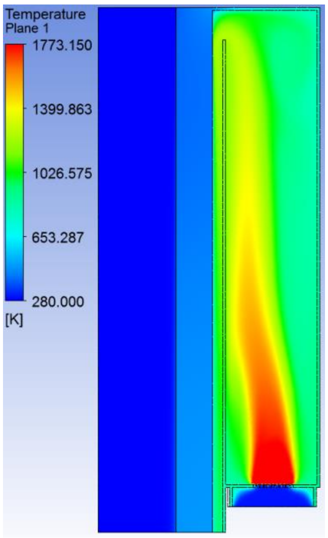


Figure 2.8: temperature axial burner

Later on the different contributions to heat flux will be discussed and the results for all four situations will be presented in table 2.1. The maximum temperature of the flame cannot be seen because of the adapted legend to a maximum of 1772 K. The flue gas temperature in the outlet of the burner is calculated as a mass flow averaged temperature of 600 K and the water temperature is calculated as a mass flow averaged temperature of 300 K in both cases.

Temperature profile:

The temperature profiles for concurrent flow and countercurrent flow are given in figures 2.9 and 2.10 respectively.

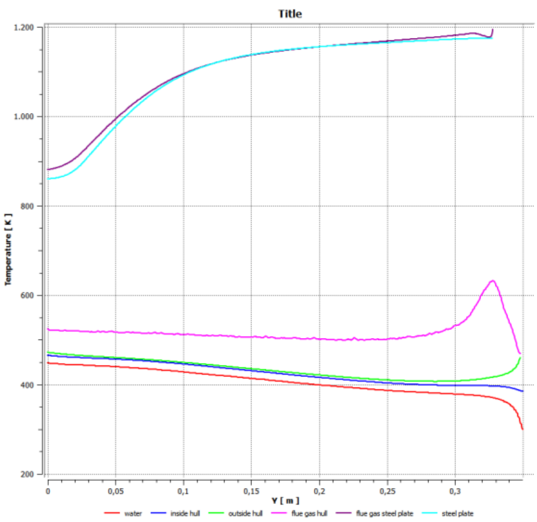


Figure 2.9: temperature radial burner, concurrent

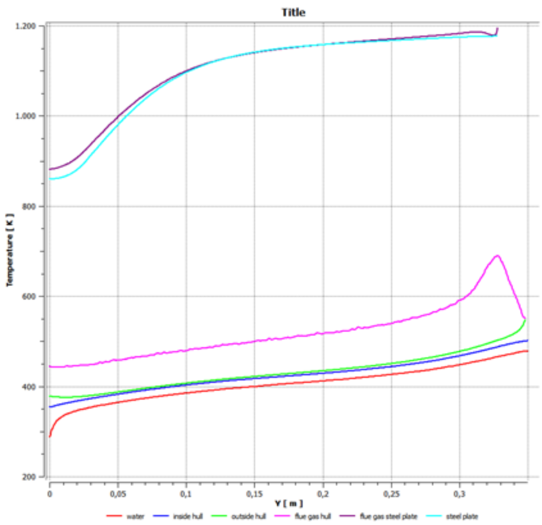


Figure 2.10: temperature radial burner, countercurrent

The temperature of the radiation plate for both cases is nearly the same and varies between 850 K and 1200 K with the highest values at the location of the flame. In case of concurrent flow the flue gas temperature is nearly constant unlike the increase of the flue gas in the case of countercurrent flow. The temperature gradient of the wall temperature and water temperature are each other's opposites as expected.

Heat transfer:

The original design of the burner was based on the optimization of the contribution of radiative heat from the radiation plate. To analyze the contributions to the heating and melting of the granules the heat balance at the wall of the barrel has to be investigated. This balance is given in equation (7).

$$\lambda_s \cdot \left.\frac{\partial T}{\partial n}\right|_{w,s} = \kappa \cdot \left.\frac{\partial T}{\partial n}\right|_{w,g} + \varepsilon_w \cdot \sigma \cdot \left(T_p^4 - T_w^4\right) \quad (7)$$

In this equation the conduction of heat through the steel barrel is given in the first term, the convective heat flux of the flue gasses is given by the second term and finally the radiation flux is given in the last term. The heat transfer coefficient in steel simply is the thermal conductivity of steel. But the heat transfer coefficient in the flue gasses does depend on the turbulent viscous- and thermal boundary layer properties and material properties like thermal conductivity, heat capacity, etc. These values are hardly to obtain from the solver output. According to the CFX user manual the ratio of the convective distribution to the radiative distribution can be found by 'wall heat flux' and 'radiative intensity'.

To increase the efficiency of the burner the idea is to increase the convective contribution by for example ribs to increase velocities and surface. This means the flue gasses will decrease in temperature and hence cool the radiation plate in temperature. Suppose the radiation plate has a temperature of 1000 K and the surface temperature of the barrel has an temperature of 500 K. It can easily be seen from equation (7) that the radiative heat flux will decrease by 40%. This means that optimizing the convective heat flux have to occur without changing the mean temperature of the radiation plate.

Efficiency:

The efficiency of the burner is defined in equation (8) as the ratio of heat transfer by to the water and the combustion heat from the fuel CH4.

$$\eta = \frac{\phi_{m,w} \cdot c_w \cdot \Delta T_w}{\phi_{m,g} \cdot H_o} \quad (8)$$

In table 2.1 some important figures from the calculation are given for four cases as concurrent - and countercurrent flow in both radial and axial burner. Based on the efficiencies it can be concluded that the radial burner and axial burner have equal efficiencies and a small difference in concurrent - and countercurrent flow in favor of the countercurrent flow as expected. The dimensions of the radial burner are limited by the flame length. This means that the distance between burner deck and the opposite wall, in this case the radiation plate, has to be larger than this flame length. Therefore, an axial burner will be preferred for compact burners.

Table 2.1: Comparison of burner types

		radial burner Concurrent	radial burner countercurrent	axial burner concurrent	axial burner countercurrent
Efficiency	%	55.7	57.1	55.7	57.0
Flue gas temperature	K	914.9	907.8	911.1	903.5
Water temperature	K	283	283.1	283	283.1
Temperature radiation plate	K	980.9	981.7	926.5	928.9
Radiative heat flux	%	66.1	66.2	67.6	67.0
Convective heat flux	%	33.9	33.8	32.4	33.0

Volumeflow (CH_4)	0.0941 m^3/s	Heating value (CH4)	35882 kJ/m^3
Massflow (water)		Heat capacity (water)	4.2 kJ/kgK

The water temperature and flue gas temperature show hardly any difference. The small differences in flue gas temperature have to be assigned to conductive heat losses in the metal parts although the walls have been specified as adiabatic. In all cases, the radiative heat flux is substantially greater than the convective heat flux and approximately 67% of the total flux. Remarkable is the lower temperature of the radiation plate in case of the axial burner although the radiative heat flux is slightly higher. To explain this discrepancy one has to keep in mind that in table 3.1 the mean value of the temperature is given and the heat flux is dependent on local temperature differences and thus on the temperature profiles presented in figure 3.9.

2.3.4 EFFICIENCY IMPROVEMENTS

In the previous section, it is proven that the radiative contribution of the heat transfer is dominant with respect to the convective contribution. The radiation is mainly dependent on the temperature of the radiation plate. In order to investigate the sensitivity of the temperature of the radiation plate, two computational experiments have been carried out. First, the position of the gas inlet chamber and hence the location of the flame has been examined. Secondly, the fins, see figure 2.1, on the radiation plate are extended to the barrel surface to make thermal contact between the radiation plate and the barrel.

The results of these investigations are reported in [b]. It is important to note that the dimensions of the numerical model are based on an injection molding machine with a barrel diameter of 79 mm and hence the results of section 2.3.3 should not be compared one on one.

Variation in flame location:
In table 2.1 the temperature of the radiation plate and the temperatures of the flue gasses are almost the same. Both mean temperatures are approximately 900 K with the highest values for the radiation plate at the location of the flame. This means, that the flue gasses carry their heat to the barrel. But, on the other hand the flue gasses will also be heated up by radiation from the hot radiation plate. This effect limits the cooling of the flue gasses. The idea to reduce this effect is to position the gas inlet chamber more towards the end of the combustion chamber. At the position of the chimney, the radiation plate will be cooler and hence a reduction in flue gas temperatures will be achieved.

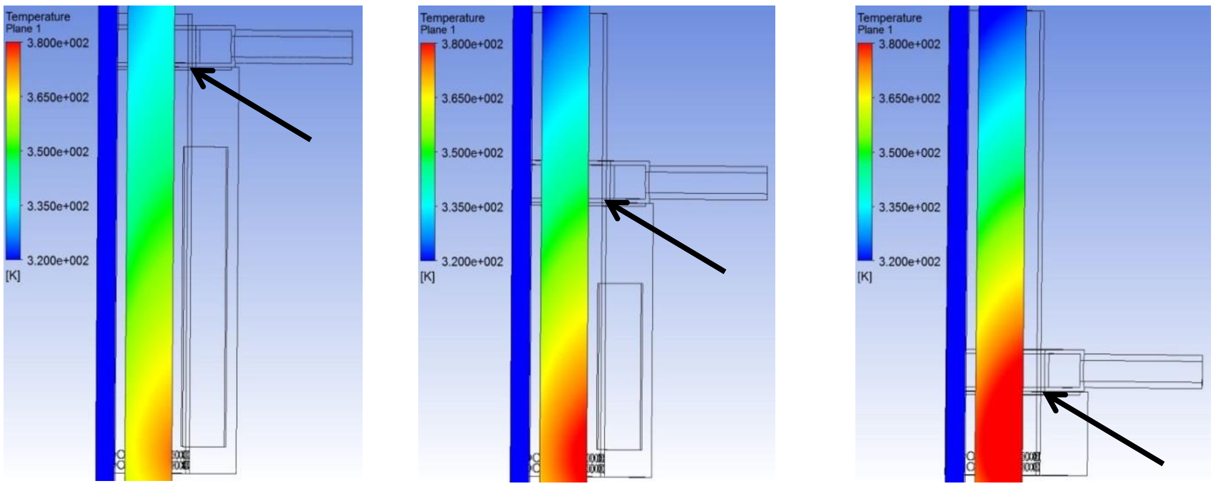


Figure 2.11: Temperature of the barrel with different positions of the flame. The positions of the burner plate are indicated with an arrow

Three positions, ranging in axial direction see figure 2.11, of the gas inlet chamber have been examined. The calculations show that the temperatures of the flue gas were equal in all three cases. The calculated efficiencies were about 41.5%. The most remarkable differences are the temperature profiles of the barrel. These temperatures vary from 320 K till 380 K. But, in the case with the lowest position of the gas inlet chamber, the local barrel temperatures are the highest. For the purpose of the heating & melting plastics, a constant temperature is desired and hence a position of the gas inlet chamber as high as possible is preferable.

Thermal contact between radiation plate and barrel:

To increase the efficiency of the burner, the heat of the radiation plate can be transferred to the barrel by conduction through a thermal contact between the radiation plate and the barrel. To investigate this effect, the fins on the radiation plate to guide the flow in the combustion chamber were extended to the barrel surface. In the simulations this can be done easily by assuming perfect thermal contact. In practice this is more complicated due to expansion of the plate at high temperatures.

To show the effect of the thermal contact between the radiation plate and the barrel surface, a cross-section of the radiation plate halfway in axial position of the burner in figures 2.12 and 2.13.

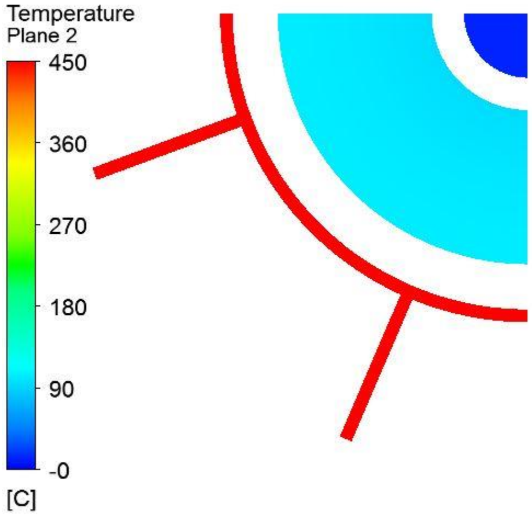


Figure 2.12: Temperature radiation plate without thermal contact

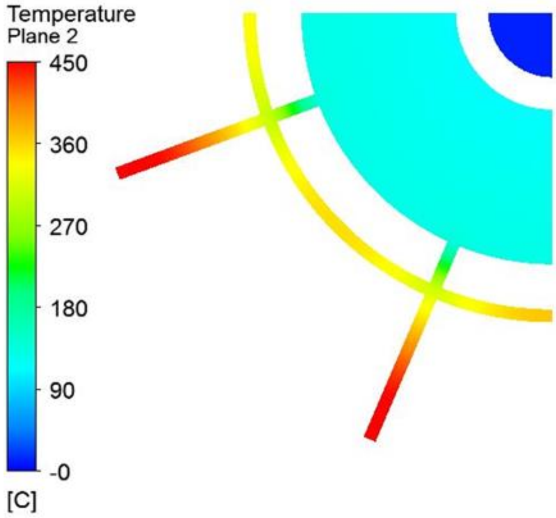


Figure 2.13: Temperature of the radiation plate with thermal contact

The temperature of the radiation plate, see figure 2.13, increases in radial due to conduction and the temperature of the plate is considerably lower than the temperature of the plate in figure 2.12. The outlet temperatures of the water flow was 17.8 °C in case of conduction of heat and 15.1 °C in case of no conduction. The increase of the water temperature with 2.7 °C means that the efficiency will increase with 6.5% to 48%.

2.4 CONCLUSIONS

This chapter clearly shows the benefits of numerical simulation with respect to experimental observations. Detailed information, like temperature profiles, velocities and pressures, can be obtained for all locations, which is hardly or not even possible in experiments. This will increase the understanding of the physics in the combustions process and will lead to improvements with respect to design. On the other hand one has to be careful with quantitative interpretation of the results because assumptions had to be made, for example for the emissivity and adsorption coefficients.

With respect to the burner it can be concluded that the axial burner and radial burner are similar with respect to efficiency. This gives the opportunity to develop burners for smaller injection molding machines with respect to the rule of thumb for the maximum flame length. The efficiency will decrease considerably with smaller dimensions of the burner. The small differences in countercurrent and concurrent flow provide flexibility in mounting the burner on a machine. Also, it is proven that the heat transfer is dominated by radiation rather than convection. Increasing the convective contribution to the heat flow has to be done with care with respect to the accompanied decrease of the radiation heat flux.

References

[1] Tu, J., Yeoh, G.H. and Liu C. (2008) Computational Fluid Dynamics, a practical approach.

[2] Versteeg, H.K. and Malalasekera, W. (1995) An Introduction to Computational Fluid Dynamics, The Finite Volume Method.

[3] Poinsot, T. and Veynante, D. (2005) Theoretical and Numerical Combustion, Edwards, ISBN 1-930217-10-2.

[4] Magnussen, B and Hjertager, B.H. (1976) 16th symposium (int.) on combustion, 719-729, The Combustion Institute, Pittsburgh

[5] Frassoldati, A., Cuoci, A., Faravelli, R., Ranzi, E., Candusso, C. and Tolazzi, D. (2009) Simplified kinetic schemes for oxy-fuel combustion, 7-8, Dipartimento di Chimica, Materiali e Ingegneria Chimica, Politecnico di Milano, Italy

[6] Lin Wang, Zhaohui Liu, Sheng Chen and Chuguang Zheng: (2001) Comparison of different global combustion mechanisms under hot and diluted oxidation conditions, 11-13, State Key Laboratory of Coal Combustion (SKLCC), Huazhong University 5 of Science and Technology, Wuhan, China

[7] Incropera, .F.P., DeWitt, D.P., Bergman, T.L. and Lavine, A.S. (2006) Fundamentals of Heat and Mass Transfer, John Wiley & Sons, ISBN-13: 978-0-471-45728-2

Internal reports

[a] Hummel, C. (2013) CFD analysis of heating in a gas burner for injection molding, University of Applied Sciences Windesheim, Polymer Engineering.

[b] Hummel, C. (2014) Gas heated injection molding, radiation and convection, University of Applied Sciences Windesheim, Polymer Engineering.

3 Use of alternative and sustainable energy sources

Buist, J., Hummel, C., and Groen, R.

In the plastic processing industry, for example in injection molding machines, electrical heating is the most common way to heat and melt plastic granules. An alternative to electrical heating is a heating system based on the combustion of natural gas. This system is introduced in order to reduce the CO_2 production and to save energy costs. The basic idea behind this change to a gas heated system is explained in section 1.2 and references [1] and [2]. A failure analysis of the original design is given. Based on this analysis the burner is redesigned. With respect to confidentiality, not all the details, like geometry, dimensions and materials, of the design are given. Finally, the improvements of the design are validated with numerical simulations and experiments.

3.1 FAILURE ANALYSIS (ORIGINAL DESIGN)

To evaluate the possible cause of the observed initial cracks the design of the burner has been analysed by calculating the thermal stresses using a finite element method (FEM) based on the temperature field obtained by CFD calculations, see [a]. In this study, the result of the calculations will be compared with the observed mechanical deformations of the dismantled burners, which had been operational for several years. In section 4.3, the same procedure of numerical calculations will also be used to design a new burner with lower thermal stress values. When the locations of high thermal stresses in the calculations coincide with the locations of cracks in the visual inspection, the numerical method can be considered as validated for the design of the new burner.

3.1.1 VISUAL INSPECTION

In this section photos of a dismantled burner are shown in figure 3.1 and 3.2. In the original design all components of the burner, like radiation plate, combustion chamber, housing, gas inlet and burner plate, are welded together to form one part, see figure 3.1.

Figure 3.1: Cross section of the heater (original design)

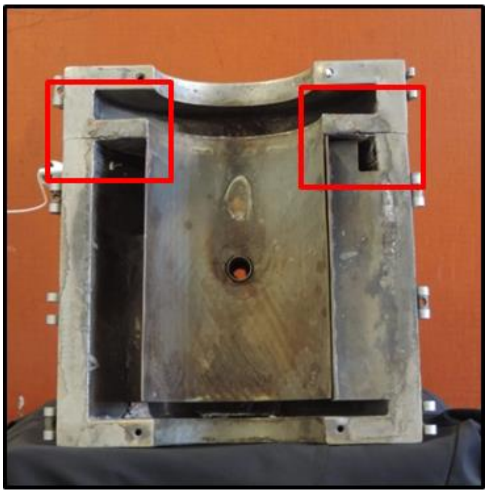


Figure 3.2: Cross section of the heater (original design)

However, these components have different temperatures during operation, for example the gas inlet and the radiation plate. The gas inlet is cooled by the inflow of a relatively cold mixture (300 K) of natural gas with air and the hot (900 K) radiation plate is heated by the flame in the combustion chamber. The construction clearly shows the initiation of crack formation at the connection of the gas inlet and the radiation plate; see the red areas in figure 3.2. Also weld cracks can be observed, where different materials were welded together.

The cracks can be classified in two basic types of cracking: weld cracking and corner cracking. It was observed that the welds have been grinded in order to obtain flat contact areas, resulting in thin welds. Thin welds caused by grinding have weakened the construction on several locations, leading to local stress increase. Grinding away the welds needs to be avoided, i.e. by improved weld design such as corner welding inside the construction. Grinding is only allowed on the opposite side of the weld.

Thermal stresses are assumed to be very high, given the high burning temperature of the fuel. Thermal stress in combination with stress concentration in corners is expected to be the main cause for corner cracks. The issue of thermal stress is going to be discussed further in section 3.1.2.

3.1.2 NUMERICAL STRESS ANALYSIS

Earlier CFD-studies [a] on the original design of the heater have resulted in temperature profiles. The temperature profile for the cross section is presented in figure 3.3. The temperature profiles were used as input data for FEM-analysis of the structure, using the Ansys program.

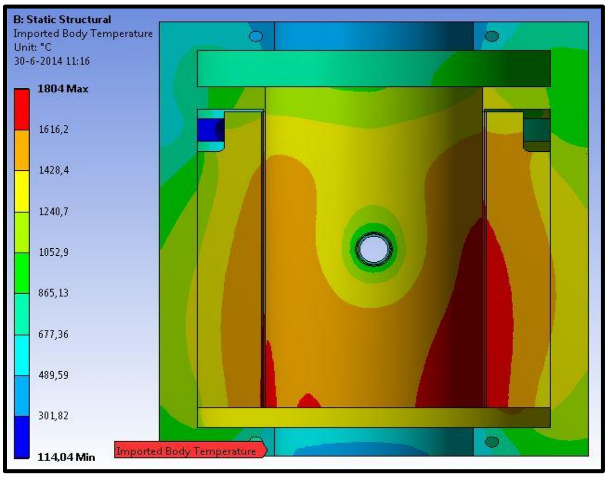


Figure 3.3: Temperature profile of burner (original design)

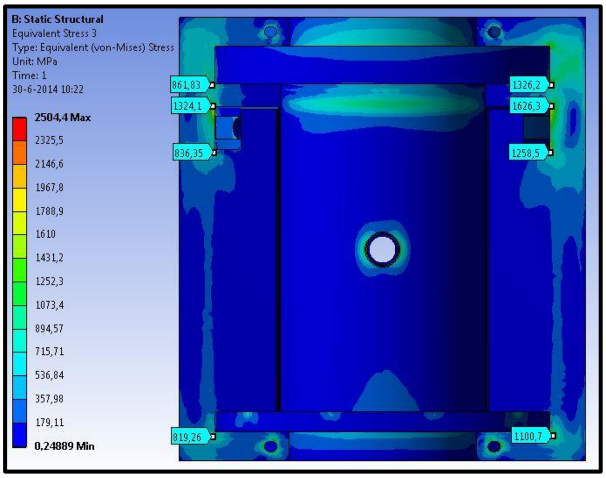


Figure 3.4: Thermal stress FEM-analysis (original design)

The maximum temperature of the hull, calculated by the CFD-analysis, is around 1600 °C. In the area where cracks were observed, the maximum temperature is in the range of 670 °C up to 1050 °C. It is noted that the temperature gradients at the hot spots are steep. This is expected to lead to significant differences in thermal expansion, resulting in high local stresses.
The output of the thermal stress FEM-analysis is presented as a plot, indicating the levels of calculated stress, see figure 3.4.

The thermal stress analysis shows von Mises stresses on the location of the actual corner cracks ranging from 836 up to 1600 MPa. This is way beyond the allowable stress of 515 MPa for the applied materials. The highest stress levels on the left (1324 MPa) and the right (1626 MPa) are exactly in line with the locations of the actual cracks in the tested hull.

It is noted that in most locations, stress levels are in the range of up to 357 MPa, below the allowable stress. Stress levels around the bolting holes are high too. This coincides with heavy deformation of the bolting holes in the tested burner.

3.1.3 CONCLUSION FAILURE ANALYSIS

The observations of the visual inspection are in line with the results CFD/FEM-analysis. This provides enough confidence in the numerical procedure to optimize the design of a new burner with CFD simulations for the temperature field and FEM analysis of the thermal stresses.

3.2 REDESIGN (STRESS FREE)

The possibilities to develop a burner for the Engel (50 tons) injection molding machine were examined in [b]. The dimensions of the burner had to be suitable to mount it on this machine. The diameter of the barrel of that machine is 78 mm, which dictates the inner diameter of the burner. The outside of the burner has to be smaller than 172 mm with respect to the guiding system of the machine. This gives a total space of 47 mm in radial direction for the total burner. This space has to be divided in shielding, combustion chamber and spacing (7 mm) between radiation plate and barrel for the returned flow of the flue gasses. Due to these small dimensions the decision was made to develop an axial burner instead of a radial burner as in the old design. In chapter 2, it is proven that both types have comparable efficiencies.

In the previous section the cause of the high thermal stresses were attributed to the fixed contacts of all the different components (especially contacts between hot and cold components). In order to avoid these fixed contacts, the burner now is divided into different components, which can expand independently due to temperature differences. The space between the components is determined based on the calculated temperatures in the old burner and corresponding thermal expansions. The components are indicated by different colors in figure 3.5 for one half of the burner. The burner is split into two halves in order to mount it on the barrel of the injection molding machine. The red color represents the radiation plate (1000 K), the yellow color the gas inlet system (300 K) and the grey color the housing of the burner (400 K on the outside and 800 K on the inside).

The design of all components will be explained in the following sections. Details of the construction will not be shown for confidentiality reasons. Finally, in section 3.2.4 the design was checked with a full CFD simulation and a FEM analysis with respect to thermal stresses.

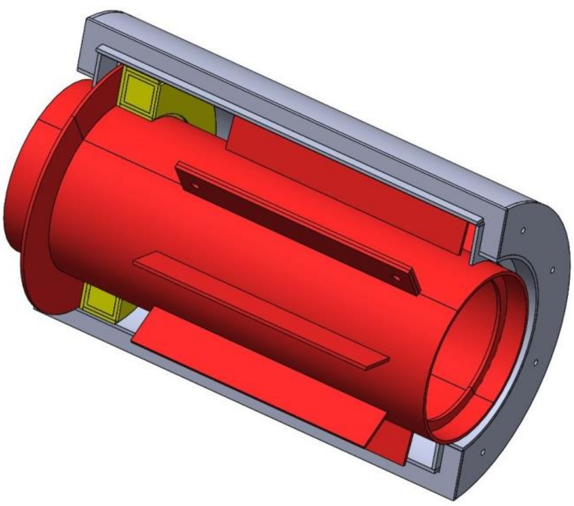


Figure 3.5: Redesign of the heater with components divided in colors

3.2.1 HOUSING

The housing (figure 3.5 in grey and figure 3.6) is still a component that contains both hot and cold surfaces. Between the inside and the outside of the housing a layer of insulation is mounted. This ensures that the outside of the housing is relatively cold, but the inside of the housing is relatively hot. The design of the housing allows expansion of the hot inside of the housing separately from the cold outside of the housing in order to prevent thermal stresses. The expansion of the housing can however cause leakage of the flue gases. To prevent this leakage the spaces between the two halves of the burner are closed with gland packing.

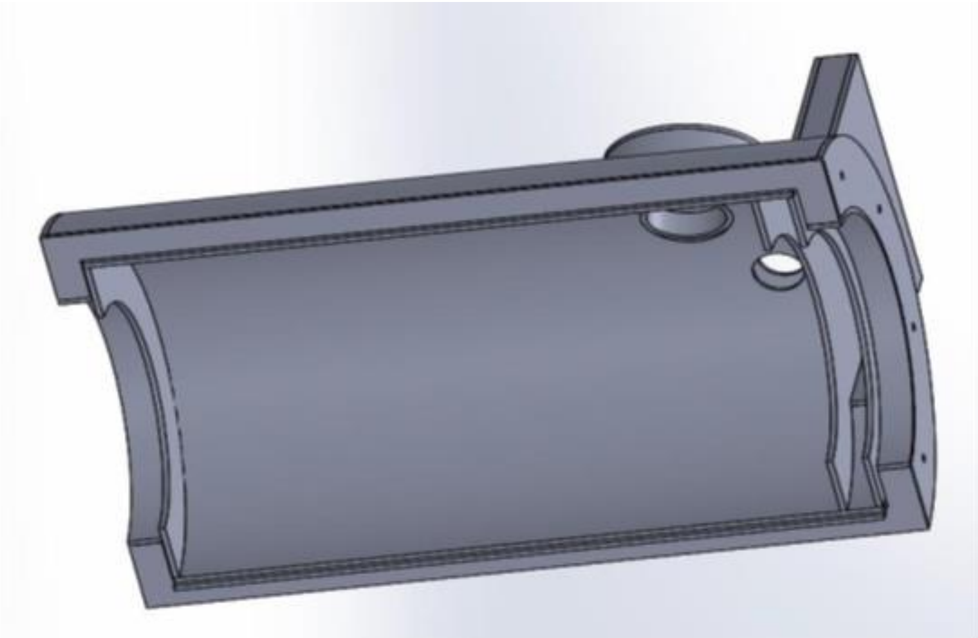


Figure 3.6: Housing

3.2.2 RADIATION PLATE

The radiation plate (figure 3.5 in red and figure 3.7) is the hottest component of the heater. The function of this plate is to shield the barrel of the injection molding machine from the flame in the combustion chamber. Because of its high temperature, the plate is designed to have no fixed contacts with the housing, the combustion chamber, the gas inlet chamber and the barrel. This way the total radiation plate can expand without any restrictions and hence it is free from most of the thermal stresses. Due to the expansion of the radiation plate a small gap will occur during operation between the support of the plate on the barrel and the barrel itself. Leakage of flue gasses is prevented by filling of the space between the barrel and the radiation plate with gland packing on both sides.

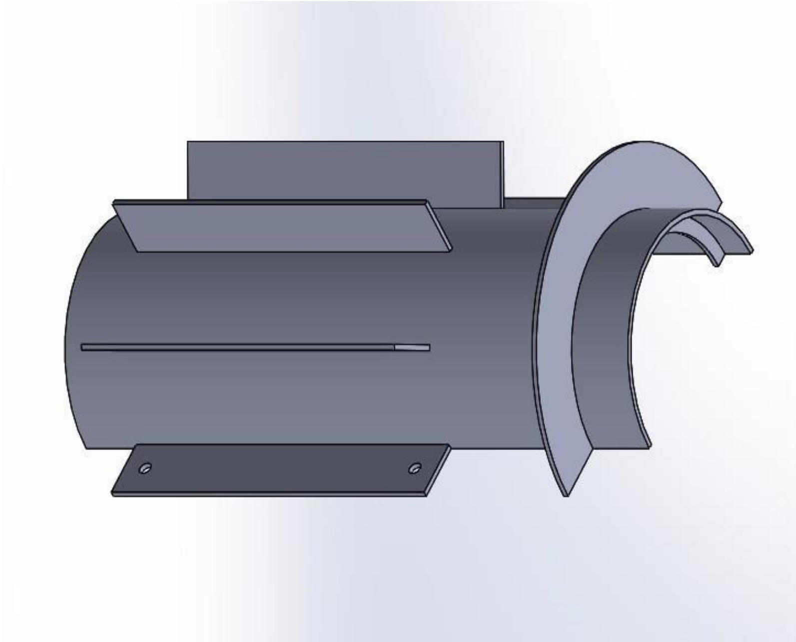


Figure 3.7: Radiation plate

3.2.3 GAS INLET CHAMBER

The combustion chamber (figure 3.5 in yellow and figure 3.8) is a component cooled by the flow of the gas mixture. It is of great importance that the gas inlet chamber doesn’t get too hot because of the danger of igniting the gas mixture inside the chamber. The gas inlet chamber does not have material contact with the hot radiation plate nor with the warm inside of the housing. Heat conduction to the gas inlet chamber from for example the radiation plate is prevented by sheets of insulation between the surfaces. The lower part, the burner plate, of the inlet chamber consists of a perforated plate with small holes, which are covered by knitted surface material.

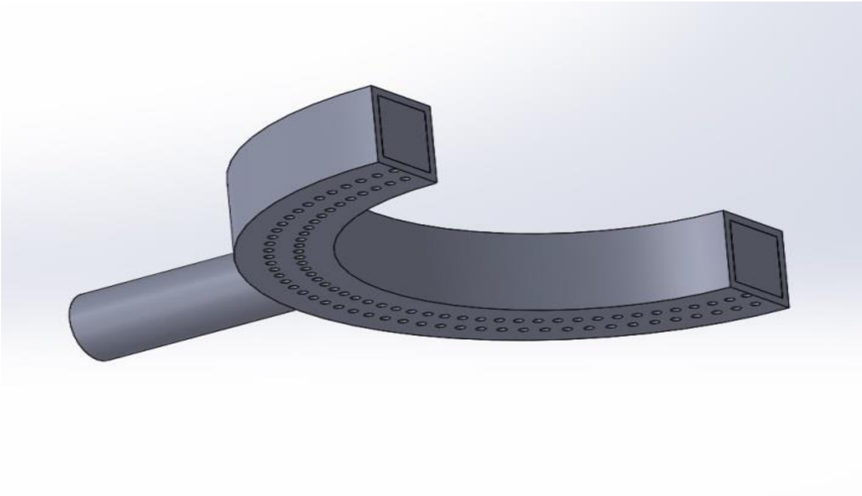


Figure 3.8:Gas inlet chamber

The inlet chamber is designed to evenly distribute the gas mixture over the heater. To check the distribution, a visualization test was carried out by operating the inlet chamber separately in the ambient air, see figure 3.9. In figure 3.10 a CFD calculation of the gas flow through the inlet chamber is shown.

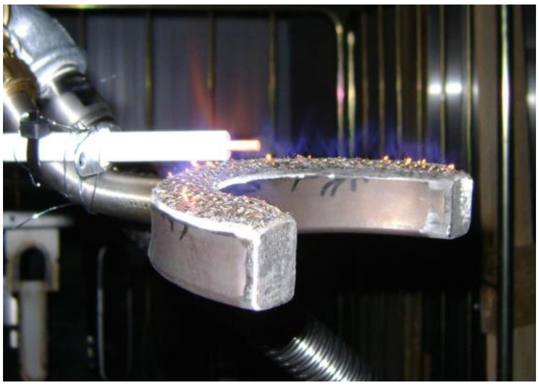


Figure 3.9: Visual test of flame

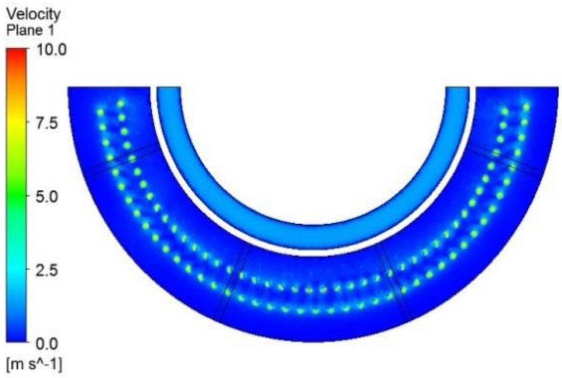


Figure 3.10:Velocity profile

The flow through the small holes results in a large pressure drop over the plate compared to the total pressure drop of the burner. Due to this relatively large pressure drop a good distribution of the flow is assured. Both figures show a correct distribution of the gas mixture over the burner plate without any no velocity peaks.

3.2.4 NUMERICAL MODEL

The analysis in chapter 2 mainly took place with only a slice of the burner which was enough to investigate important features like efficiency, the ratio between radiation and confection and the difference between axial flow and radial flow. In order to investigate thermal stresses and asymmetry in flow distribution in the two halves, a full 3D model of the burner has been developed, as shown in figure 3.11. With respect to computation time the number of histories in the Monte Carlo calculation, see section 2.3.2, for the radiation is limited (with full radiation computation time will be more than a week). Notwithstanding this limitation, the predicted temperatures are expected to be reasonably accurate.

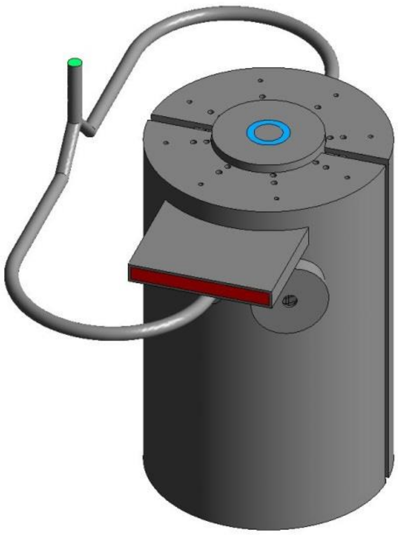


Figure 3.11: Assembled burner

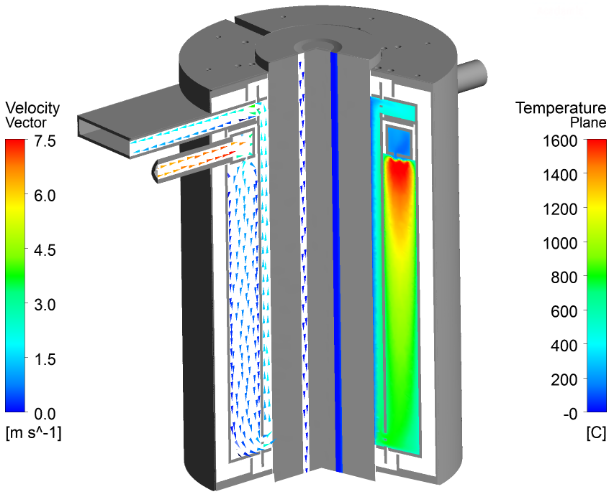


Figure 3.12: Velocity field and temperature field

In this picture it can be seen that the burner only has one chimney (red opening) and has a gas inlet on both sides of the burner, which will be fed by one premixed gas system (green opening). The plastic flow in the barrel, modeled by either water or thermal oil, is also shown (blue opening).

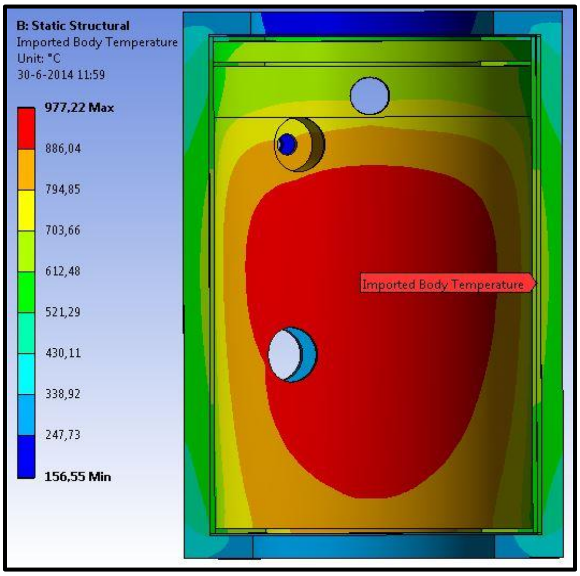
The burner is a premixed burner with a mass flow of 1.114 g/s 'Groningen' gas (CH_4, O_2, N_2 and H_2O) and with an air excess of 25% (□ = 1.25). The total power of the burner is 3.8 kW. This is enough to cover the total heat requirement of the machine with two burners, taking into account the efficiency of the burner. The functional tests of the burner were carried out with water, see section 3.5.1. A mass flow of water of 24.62 g/s, with an input temperature of 12 °C, is specified in the barrel. This high flow rate ensures a small increase in water temperature and hence save operation of the burner.

The results of the simulations are given in figure 3.12, with on one side the velocity field and on the other side the temperature field. It can be seen that the velocities are low (average less than 1.5 m/s) in the burner. The highest values (7.5 m/s) are found in the gas inlet chamber and reasonable velocities (3.0 m/s) in the spacing between radiation plate and barrel. The maximum flame temperature is 1600 °C, which is below the maximum flame temperature (1875 °C) of a stoichiometric mixture, see [3]. The temperature in the gas inlet chamber is below 100 °C as can be seen in the figure. The calculated pressure drop in the burner is 57 Pa, which is acceptable for the fan in the gas system.

3.2.5 THERMAL STRESS ANALYSIS

Based on the observed cracks in the original design of the heater, the construction has been redesigned to improve the thermal stress resistance of the hull. The improved design has been analyzed, using the same numerical procedure described in section 3.1.2. The temperature profile of the heater under working conditions was calculated using CFD. The resulting temperature profile is used to calculate thermal stresses with FEM.

The temperature profile for the cross section of the improved design is presented in figure 3.13. This profile shows considerably lower maximum temperatures compared to the temperatures of the old design in figure 3.3. At locations prone to corner cracking, the temperature ranges from 250 °C to 600 °C.



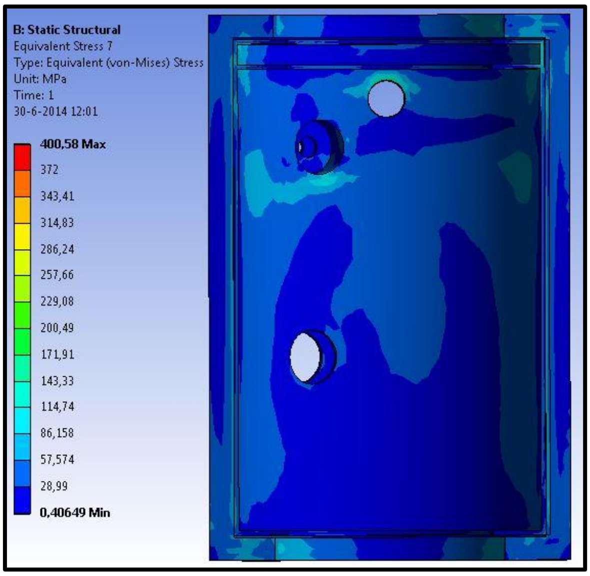


Figure 3.13: Temperature profile

Figure 3.14: Thermal stresses

Temperature gradients at these locations are lowered, which is expected to reduce local stress variations considerably. The maximum temperature found is 977 °C on the radiation plate.

The temperature profiles have been used as input data for a FEM-analysis of the structure. The output of the thermal stress analysis of the improved design is presented in figure 3.14. The analysis shows drastically reduced von Mises stresses on the corner locations ranging from virtually 0 MPa to 200 MPa. These are acceptable stress levels, considering that the allowable stress is 515-680 MPa. This coincides with the absence of any cracks in these corners as observed during the visual inspection of the new burners, figure 3.17.

3.3 EXPERIMENTAL VALIDATION

Originally the idea of the project was to test the burner on an injection molding machine (Engel 50 tons) with a field test. However, due to safety and time constrains the decision has been made to start with a functional test in a gas laboratory. The performance of the burner will be measured and safety aspects will be examined. In this laboratory all equipment is available and safety measures are taken to certify the burners according to the applicable standards, directives and procedures, which will be described in section 3.3.1.

A test tube was designed to represent the flow in the barrel of the machine in section 3.3.2. First, functional tests were carried out with three burners on this test tube with cooling water, representing the melting plastics in the barrel. Secondly, one of the three burners has been tested in a duration test in order to examine the reliability with respect to thermal cracking. In this case thermal oil has been used to allow for higher temperatures approaching the melting temperature of general plastics.

3.3.1 STANDARS AND CERTIFICATION

The plastic processing industry is very restrained in using gas combustion with respect to the flammability of plastics. Therefore electrical heating has become a logical choice for heating purposes. In this respect it is important to follow the demanded standards, directives and procedures when developing and testing new gas applications.

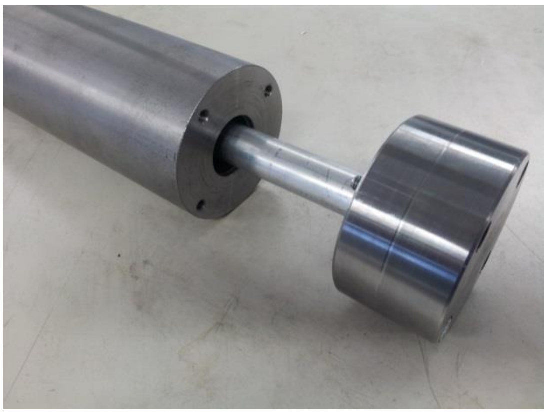
For each gas application different standards need to be applied, like NEN1020 for air heaters and NEN483 for central heating boilers, in a gas technical inspection. It goes without saying that for the application of gas heated burners for the plastic process industries no separate standard is available. Therefore the best practice of the above mentioned standards will be applied. Also the guidelines, which are included in the directives for machines, low voltage, EMC, etc., have to be accomplished before commissioning the burner in the plastic process industry. For the total systems, components like fan, controller and venturi, have been selected from proven design in the central heating industry, which ensures compliance with the standards.

During the gas technical inspection, the gas dynamic behavior of each gas device has to be judged using a standard gas, for example Groningen grade and the power has to be determined. Also the maximum and minimum chimney dimensions, length and diameter, have to be tested with different windfalls to obtain enough draft.
Besides these tests with standard gas, other test gasses will be defined, such that safe operation in deviations of local circumstances is insured. The deviations of local circumstances mainly are changing in composition of the local gas and changing properties of the combustion air like temperature and humidity. During operation of the burner on these test gasses no dangerous situations may occur like flame weft and augmented formation of CO gasses. Also the ignition of the burner has to be ensured in all circumstances.

When all test results are positive, a safe operation of the burner can be insured to safely operate the burner in an industrial environment.

3.3.2 FUNCTIONAL TEST

The extruder of the injection moulding machine is represented by a test tube with the same dimensions of the barrel of the Engel 50 tons machine with an outside diameter of 78 mm and an inner diameter of 30 mm, see figure 4.15 and [c]. The length of the tube is 300 mm which provides 15 mm space with respect to the length of the burner (270 mm).



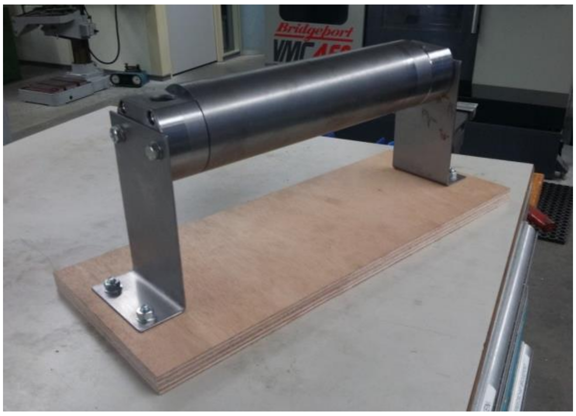


Figure 3.15: The test tube

The screw of the machine is represented by a solid rod with the same diameter of 20 mm. The profile on the screw is neglected for simplicity. On both endings a coupling was constructed for the in- and outflow of the cooling medium, such that the flow between tube and rod is uniform.

The goal of the functional test was to investigate the ability to assemble the burner, to ensure safe operation, test for possible indications for crack formation and to measure the performance of the burner. With respect to performance, only the order of magnitude of the efficiency is important in this stage. Therefore, the tests have been performed by releasing the heat of the burner by tap water flowing through the test tubes, see figure 3.16 (yellow hose pipes), without regulation of the inlet temperature.

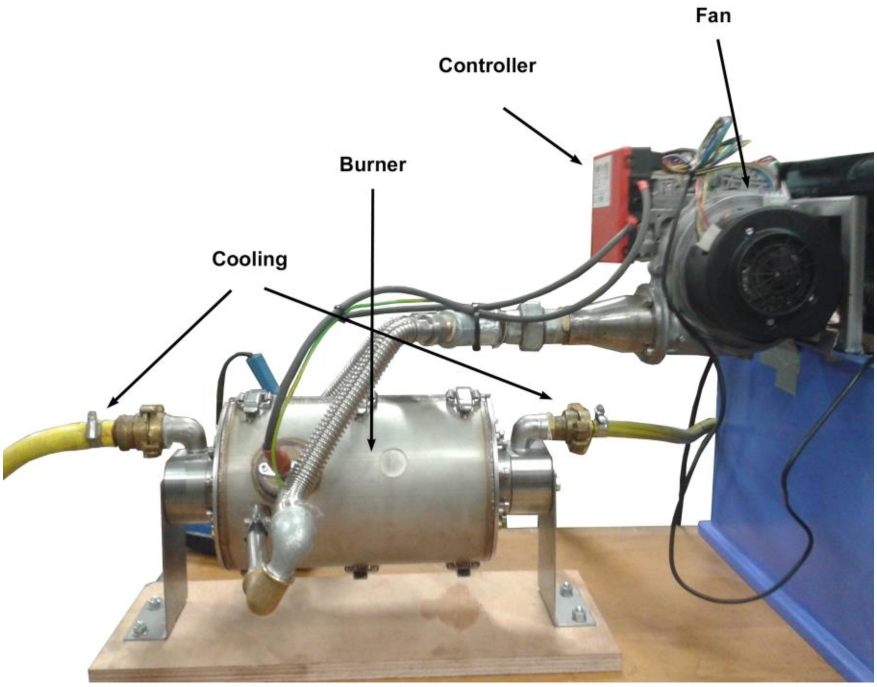


Figure 3.16: The total test set-up

The volume flow of water is chosen such that only a small temperature rise of the water will occur assuring that overheating is prevented. This results in only rough indications of the efficiency of the burner. The measured temperatures in the burner are however accurate enough to judge the safety of the burner and observe improvement with respect to crack formation in comparison with the old design. To insure the safe operation of the burner, standard industrial components (fan, venturi, gas controller, etc.) to control the premixed gas flow have been used. The ignition of the gas was started by the controller on one side of the burner. The existence of a flame on the other side was detected. If no flame was observed, the gas flow would have to be shut down.

In order to judge the ability to mount the burner on an injection molding machine, the burner has been assembled on the test rig several times. After some trials, the most optimized sequence to assemble the different components was found. The main difficulty was to place the insulation of the gas inlet chamber and the gland packing of the housing. This difficulty was solved by ordering pre-formed pieces of insulation and packing, instead of making it from sheets and strips. After these adaptions it was concluded that mounting the burner around a barrel of an injection molding machine is possible, taking into account the tight space on the machine as well.

The performance of the burner was measured by collecting tap water for 10 minutes and calculating the energy content based on the flow and temperature difference. From these rough measurements it could be concluded, see [d] that the efficiency (42%) of the burner was in line with the calculations in chapter 2. The efficiency will be further investigated in section 3.3.3.

With respect to safe operation, the burner was heated up and cooled down several times with and without disassembly in between the cycles. All these times the burner never failed, based on the flame detection, which means that the design of the burner with respect to the combustion dynamics, safety and operation is good. The leak tightness of the burner is investigated by observing possible hot flue gasses rising from the shielding. It was observed that after some time fumes, which appeared due to evaporation and burning of for example lubricants, grease and components from the gland packing and insulation, disappeared indicating leak tightness of the burner.

During the first test weeks the burner has been disassembled several times for visual inspection. A photo of the upper half of the burner, without the gas inlet chamber, is given in figure 3.17 showing the discoloration of the metal parts. During these inspections no indications for crack formation was found. Also, the discoloration of the metal indicates that the temperature never exceeded the maximum allowable levels for this material.

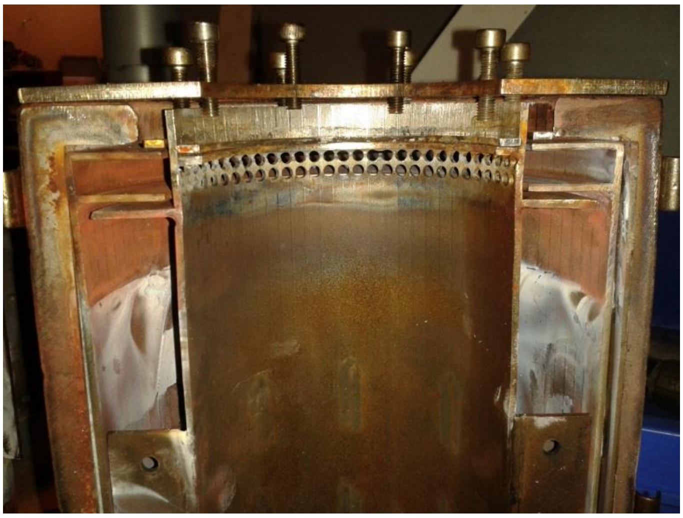


Figure 3.17: The discoloration of the burner

White deposits can be observed due to evaporation of volatile components in the insulation between the shielding and the gas inlet chamber. Despite these deposits, the function of the insulation was still intact. But, the material had to be renewed for the next assembling, because the insulation was too brittle to mount it in the next cycle.

Corrosion of the test tube, which was not made from stainless steel, was observed, indicating condensation of the flue gasses. Also from this observation can be concluded that the outside surface stayed relatively cool during the tests, since condensation of flue gasses only occurs when the temperature drops below its dew point (less than 60 °C).

The most amazing observation was a difference of the coloring on two halves of the radiation plate indication different temperature levels. Different causes for this asymmetry were proposed:

- Chimney effect: The chimney is located only on one half of the burner, which might cause an asymmetry in the flow mainly between the radiation plate and the test tube.
- Unequal flow distribution of both gas inlet chambers: The flow through the inlet chambers is determined by the pressure difference form the single gas supply to the chimney.

To investigate these possibilities the numerical model has been expanded to a full 3D model and the gas supply was incorporated, see section 3.3.4. Both investigations did not show any asymmetry in flow behavior, combustion and temperatures. Although this asymmetry did not lead to malfunctioning of the burner it had to be investigated because a more symmetrical flow might improve the efficiency. Other causes might be geometrical inaccuracies or cooling of the lower half of the radiation plate. This cooling might be due to evaporation of the condensation droplets which tend to collect only at the bottom due to gravity.

3.3.3 DURATION TEST

The test set-up for the duration test was nearly the same as for the functional test differing in cooling medium and regulation of the cooling medium; see the process scheme in figure 3.18. The system consists of two circuits. First, the barrel is cooled with thermal oil to reach higher temperatures comparable with general melting temperatures of plastics, say 200 °C. The oil is cooled with tap water in second circuit. Based on the inlet temperature of the oil, the water flow is regulated to insure a constant temperature in the test tube. For these measurements the test circuit for the original burner, see figure 3.19, was used. The circuit has an oversized cooling capacity and an on/off control system in the water flow. Due to the on/off control system, the measured temperatures of the oil were fluctuating substantially. In order to obtain stable measurements the on/off control system was therefore by-passed and the water flow was regulated manually.

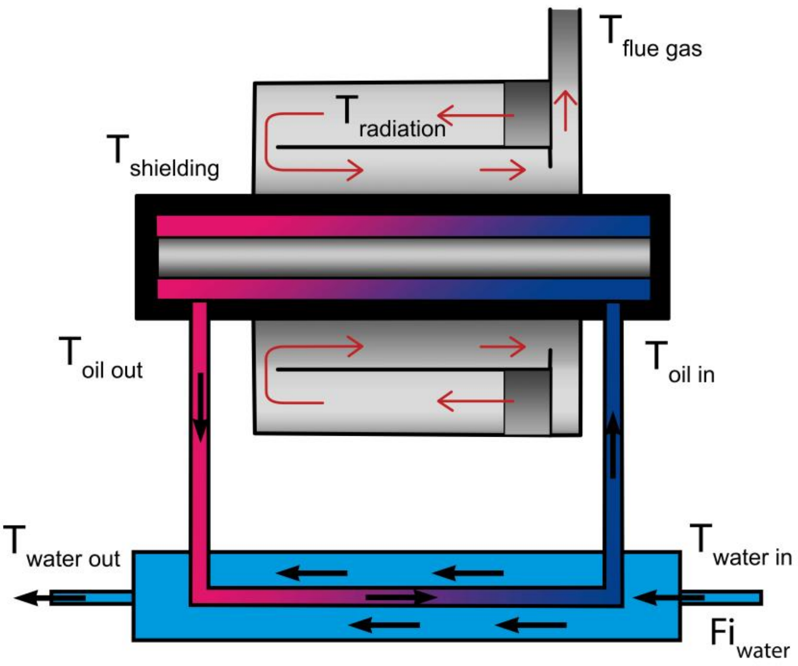


Figure 3.18: Process scheme

Figure 3.19: Duration test

To measure the flow rate the same procedure as for the functional tests was applied: tap water was collected for 10 minutes determining the flow rate and measuring the inlet and outlet water temperature.

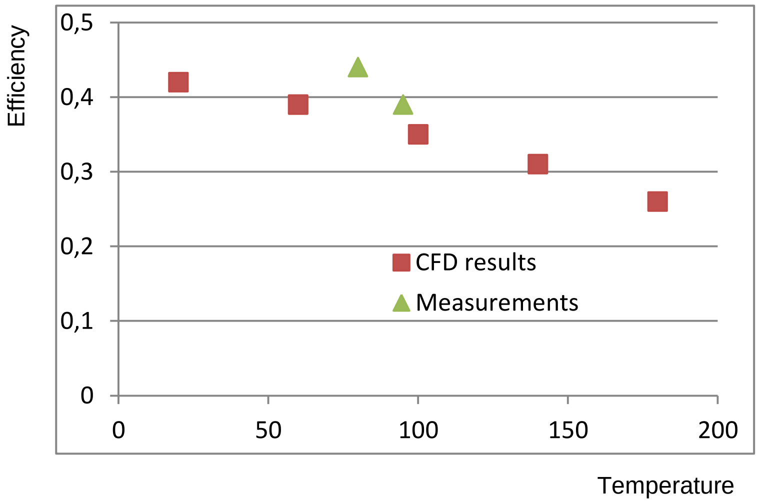


Figure 3.20: Efficiency

One of the objectives of these experiments was to obtain efficiency measurements for different constant temperatures of the oil inside the test tube. Several attempts were made, see [e], to obtain a sequence of measurements in the range from 20 °C to 195 °C. Two reliable measurements will be presented in this chapter for oil temperatures of approximately 80 °C and 95 °C, see figure 3.20.

The experiments have been carried out without sufficient insulation of the burner and the test tube, which means that adiabatic conditions at the outside of the housing are not guaranteed. Since part of the energy will be lost to the environment the efficiency based on the water temperature will differ from the efficiency based on flue gas temperatures.

In the graph 3.19 the efficiency calculated based on the water temperature is taken. To compare the experimental results with CFD simulations, the simulation have been carried out with isothermal boundary conditions (T = 300 K) on the test tube. Although, the outside of the housing of the burner was not insulated, still adiabatic conditions on the housing were applied because of the insulation between the inner and outer surface of the housing. The results of the simulations are lower than the experimental values due to the fact that the imposed temperature on the test tube was too low with respect to the measured temperatures (approximately 400 K) at the outside wall of the tube in the experiments. Finally, experiments have been carried out with full insulation of the housing and the test tube. The results showed an increase of the efficiency by 7%, see [d].

3.3.4 OPTIMIZATION

In section 2.3.3, based on CFD calculations it has been concluded that the heat transfer is dominated by radiation rather than convection. The overall efficiency of the burner could be improved by increasing the convective contribution with at least 5%, see section 2.3.4. Convection can be enhanced by increasing the surface of the barrel and blocking the flow in the channel to increase the velocity and hence turbulence. A simple way to do this is by placing an extension spring around the test tube. Based on the conclusion in section 2.3.4, it had to be kept in mind that increasing convective heat flux might decrease radiation heat flux proportionally. Therefore the height of the extension spring should be smaller than the space between the radiation plate and the surface of the test tube to prevent the spring touching the plate. In that case the radiation plate will be cooled through conduction of the colder spring.

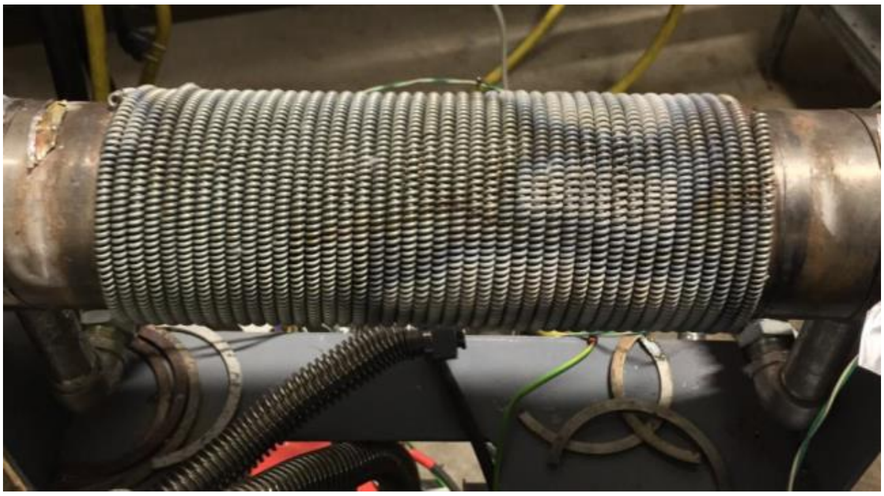


Figure 3.21: test tube with spring

In figure 3.22 a curve is presented representing the heating-up of the oil and flue gasses in case of a test tube without the extension spring and in case of a tube with extension spring. With respect to the oil temperature, no difference in temperature increase is measured. Also the spring doesn't have an effect on the efficiency of the burner. Remarkable is the increase in flue gas temperature. The most likely explanation is that the spring touches the radiation plate and the spring was heated-up resulting in a higher flue gas temperature. This observation concurs the conclusion of chapter 2, that attempts to increase the convective heat exchange have to be carried out very carefully with respect to the influence on the radiative contribution.

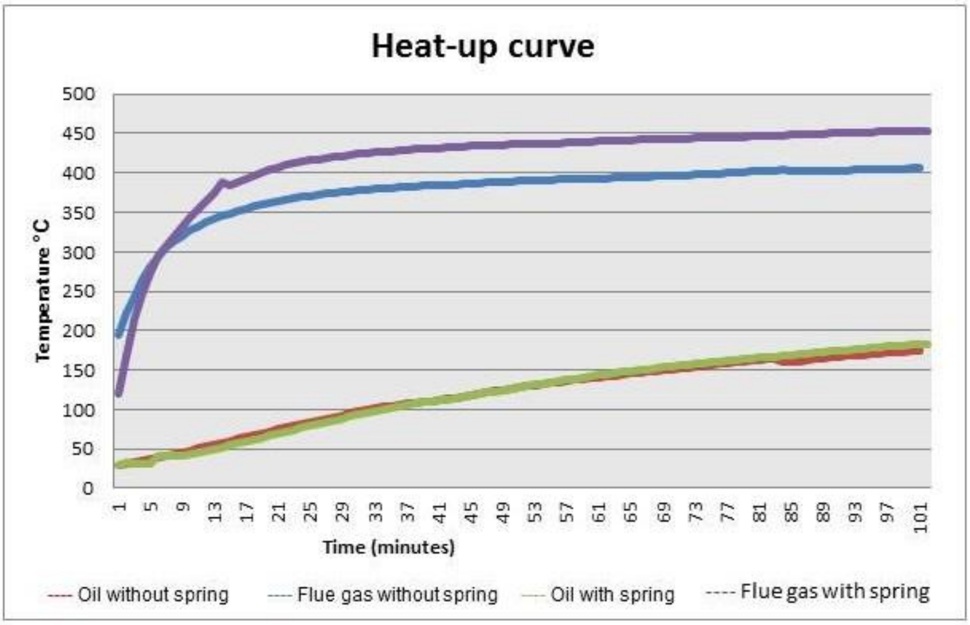


Figure 3.22: Heat-up curve for test tube with and without spring

3.4 CONCLUSIONS

The design of a gas-fired heater for melting granules in injection molding machines has been improved by numerical simulation mainly with respect to thermal stresses to prevent crack formation. This improvement was validated with numerous functional test of the burner on a test tube with tap water as cooling medium. The objective of this research, to improve the design by lowering thermal stresses, can be considered as successful and hence long time operation can be expected.

In order to obtain more than 30% saving of energy in the injection molding process, the aim to reach an efficiency of the burner of 40%. Both experimental results and numerical calculations show, that this objective can be achieved depending on the dimensions of the burner and the melting temperature of the granules.

Numerical calculation showed the potential to improve the efficiency by increasing the convective contribution to the heat exchange. Unfortunately, the efficiency measurements in the duration test were vague due to fluctuating conditions in the test circuit. Due to these instabilities the experimental results could not prove the expected improvements to increase efficiency.

References

[1] Wortberg, J. and Schroer, T. (2003) Novel Barrel Heating with Natural Gas, ANTEC event.

[2] Wortberg, J. (2010) An alternative plastification system based on natural gas, Journal of plastics technology, 6, 2.

[3] Lewis, B. and Elbe, G von (1961) Combustion, Flames and Explosion of Gases, Academic Press Inc.

Internal reports

[a] Groen, R. (2014) Gas heated injection molding, thermal stress FEM-analysis, University of Applied Sciences Windesheim, Polymer Engineering.

[b] Groen, R., Faasen, J., Vesters, H. and Teunissen, L. (2012) Gasgestookte kunststof verwarmer voor spuitgietmachines, students of the minor ‘thermodynamic engineer’ at the University of Applied Sciences Windesheim.

[c] Westerman, R. (2013) Gasgestookte kunststofverwarmer gastechnisch testen en inbouwen op de ENGEL victory50, student of the minor ‘thermodynamic engineer’ at the University of Applied Sciences Windesheim.

[d] Hummel, C. (2014) Gas heated injection molding, experimental results compared to numerical simulations, University of Applied Sciences Windesheim, Polymer Engineering.

[e] Bisschop, H and Heikoop, M. (2014) Gasgestookte granulaatverwarmer, students of the minor ‘thermodynamic engineer’ at the University of Applied Sciences Windesheim.

4 Dissemination

The work has been presented in a poster presentation, at a dedicated conference and will get follow up in a GreenPAC sponsored project.

4.1 POSTER PRESENTATION

On the occasion of the installation of Dr. M.D.C. Topp as professor for the Professorship for Polymer Engineering on February 18, 2015, the work was presented [1] as part of the program of the professorship and was summarized in a poster presentation. This was presented to more than 200 participants representing industry, institutions and government, who could inform themselves about the applied research, both past and future, at our university of applied sciences.

In the presentation of her future plans, Dr. Topp announced the program line: ‘Sustainable production’. The objective of this program line has been formulated as:

‘To acquire a firm knowledge of production processes to support the plastic industry on achieving their goals on energy savings by process optimization and innovation.’

The KOENST project forms a solid base for further development of the objectives in this line.

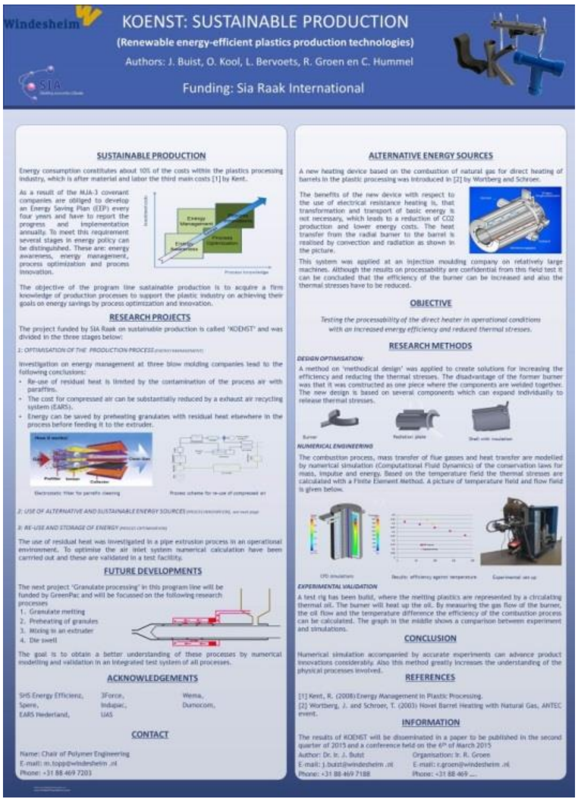


Figure 4.1: Poster presentation

4.2 CONFERENCE

On March 6, 2015 a conference was held at WAVIN dedicated to the KOENST project. In the conference room, we viewed and were inspired by their innovative solution for energy management in buildings.

During the congress, all the subjects dealt with in this book were presented by the different partners to the project. Besides these presentations, Mr. W. Wind also gave an overview of the heat and cold storage system that has been operational at the production location in Hardenberg since 1996. At this location, different processes, such as extrusion and injection molding, take place resulting in a huge demand for heating and cooling.

Finally, Dr. R. Kent gave an excellent presentation about energy management with a lot of suggestions on how to save money by implementing simple measures, such as switching off conveyor belts, installing variable speed drives and implementing proper energy management.

Figure 4.2 impression of congress

4.3 FUTURE DEVELOPMENTS

Based on the work done on the KOENST project, a new project proposal has been written. This project has been accepted by the GreenPAC Centre of Expertise, which is a joint initiative by Stenden University of Applied Sciences and Windesheim University of Applied Sciences.

The goal of the project is to obtain a better understanding of all energy processes in the plastic processing industry through numerical modelling and validation of these processes in an integrated test system as shown in figure 4.3.

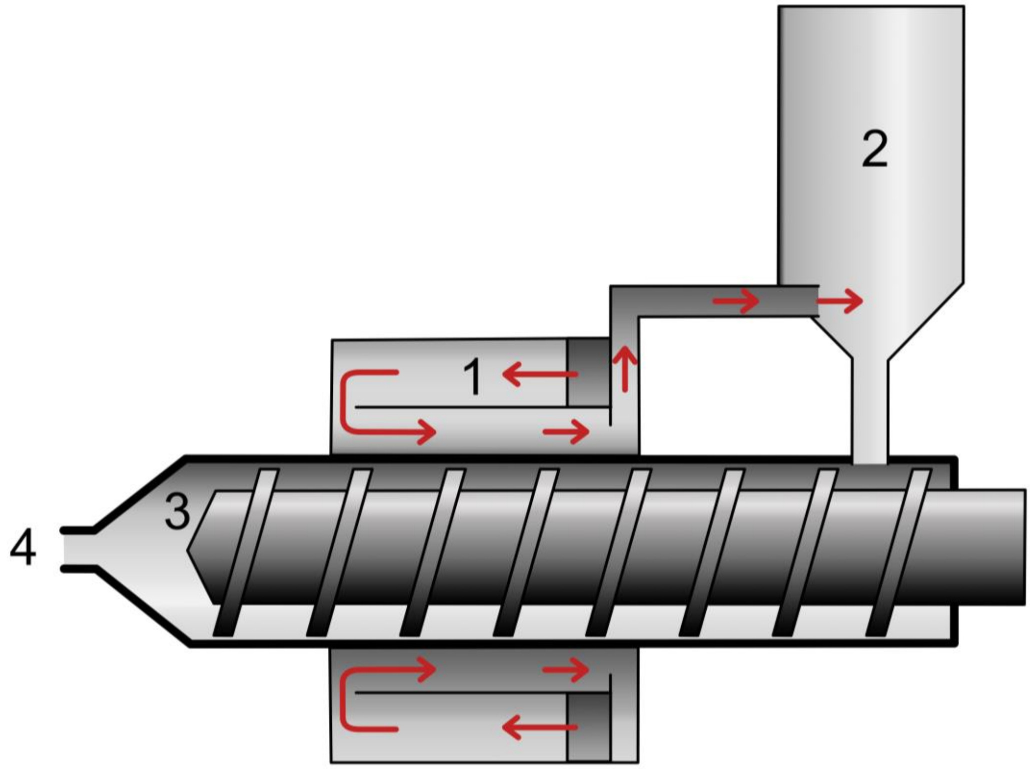


Figure 4.3: Scheme for future developments

For the next two years the following projects and research questions have been defined:

1 Melting: How to use alternative energy sources to improve and control granulate melting?
2 Preheating: How to reuse the residual heat from, for example, cooling processes for preheating the daily stock of granules?
3 Blending: How to improve mixing in an extruder to obtain a homogeneous melt in the die with respect to temperature and composition?
4 Extrudate swell: How to predict the final product shape, given a known geometry of the die, as a result of the extrudate swell?

References

[1] Topp, M.D.C. (2015) From monomer to macromolecular network: the plastic hotspot, Windesheimreeks kennis en onderzoek nr. 55.

Acknowledgements

We would like to thank the following persons and organizations for their help, knowledge, funding and efforts, which have resulted in a successful project:

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We would also like to thank Prof. Dr. J. Wortberg (Universität Duisburg), Dr. K. Saul (Universität Duisburg), Ir. J. Lodema, Dr. Ir. H. Gankema, Drs. F. Hoetink and Mr. G.J. Scholten for the fruitful discussions while writing the project proposal and formulating the research questions.

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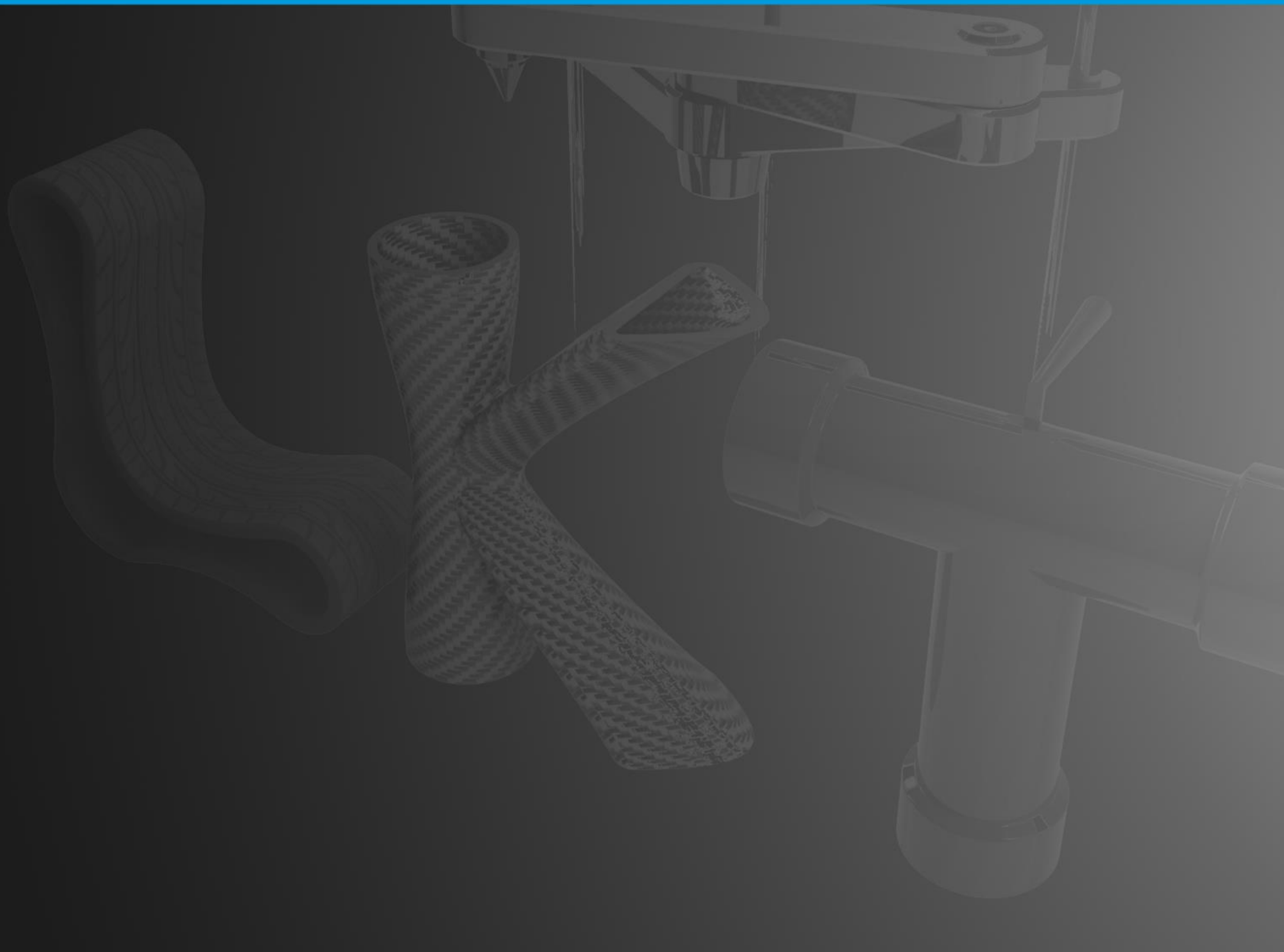
Finally, we thank both teams, the Professorship for Polymer Engineering and the school for Mechanical Engineering, for their support (moral, discussions and pleasure) in an inspiring environment. In particular, we would like to mention Margie Topp, Niels Boks and Ewoud van der Koogh for their feedback on the manuscript and Tjalke Zijlstra for the graphic design.

Websites

www.regieorgaan-sia.nl
www.uni-due.de/kkm
www.wavin.com
www.3force.nl
www.indupac.com
www.dionlocatiediensten.nl
www.earsnederland.nl
www.windesheim.nl/kunststoftechnologie
www.shs-energieeffizienz.de
www.tangram.co.uk
www.wema.de
www.sphere-nederland.nl
www.dumocom.nl
www.fhtperslucht.nl

Windesheim makes knowledge work

Professorship for Polymer Engineering



Windesheim