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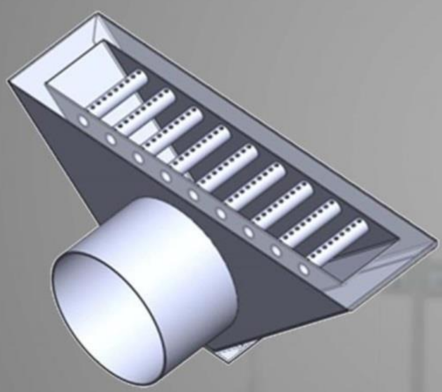
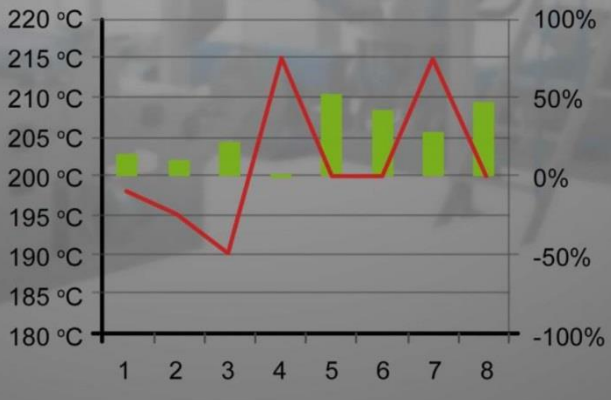
KOENST PART 2

SIA Raak International Renewable energy-efficient plastics production technologies

$$\frac{g\rho_f\left(\rho_p-\rho_f\right)d_p^3}{\mu^2}=\frac{150\rho_f\left(1-\varepsilon\right)d_p}{\varphi^2\varepsilon^3\mu}\times u_0+\frac{1.75\rho_f^2 d_p^2}{\varphi\varepsilon^3\mu^2}\times u_0^2$$





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Author : Dr. Ir. Jakob Buist
Co-authors: Dr. M. Spitz, Dr. G. Hiesgen, Ir. L. Bervoets, Ir. O. Kool, C. Hummel
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P.O. Box 10090, 8000 GB Zwolle, The Netherlands

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.

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, this document, will cover the other two areas, energy optimization of production processes and re-use and storage of residual heat..

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 more on energy innovation. At this stage in developments, considerable process knowledge is required and large investments in time and resources are expected.

In the context of 'energy-optimization’ a start is made in chapter two with the analysis of the energy consumption in a number of production processes, such as compressed air use in bottles blowing, extrusion of granulate in film blowing and the re-use of waste heat. The purpose of this analysis is to find opportunities for innovative solutions in energy reduction. As part of this analysis, the energy consumption was measured in the different zones of the extruder on two separate days and with different outside temperatures (approx. a 20°C difference). The difference in energy consumption gave rise to more in-depth research into the possibilities of preheating granulate in production processes such as film blowing and pipe extrusion. Complications in this process are the pollution of the air from the cooling processes with paraffin and bridge formation of the granules in the silos for the daily stock. It was also concluded that a thorough knowledge of the rheological processes in the different zones of the extruder is necessary to find the optimal temperature settings for these zones. Taking into account these complications, by preheating granulate a significant energy reduction can be obtained during the production of films, pipes and bottles.

In chapter three the possibilities for the re-use of waste heat for preheating granulate are examined. The numerical technique, as presented in part 1, is used to optimize the geometry of the hot air intake in a silo with granulate. A stipulated design condition is that the condition of the granules in the silo must be a so-called 'incipient' bed rather than a full 'fluidized’ bed. The numerical simulations were, subsequently, validated in an experimental test facility. The experiments show that the different stages (packed, incipient and fluidized) of fluidization can be achieved under stable conditions. This demonstrates that, in the existing design, the air distribution in the bed is sufficiently homogeneous.

In chapter four, the energetic benefits for preheating granulate are demonstrated in a field test in a pipe-extrusion process. This research shows that, through the use of waste heat, 10% energy savings can be achieved in this process.

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 het kader van 'energie-optimalisatie' is in hoofdstuk twee gestart met het analyseren van het energieverbruik van een aantal productieprocessen zoals persluchtgebruik in flessenblazen, het extruderen van granulaat bij folieblazen en hergebruik van restwarmte. Het doel van deze analyses is mogelijkheden te vinden voor innovatieve oplossingen in energieverlaging. Onder anderen is op twee dagen met verschillende buitentemperaturen (ca. 20 °C verschil) het energieverbruik gemeten in de verschillende zones van de extruder. Het verschil in energieverbruik gaf aanleiding tot een diepgaander onderzoek naar de mogelijkheden van voorverwarmen van granulaat in productieprocessen zoals folieblazen en pijpextrusie. Complicaties in dit proces zijn de vervuiling van de lucht uit de koelprocessen met paraffinen en brugvorming van het granulaat in de silo's voor de dagvoorraad. Tevens werd geconcludeerd dat gedegen kennis van de reologische processen in de verschillende zones van de extruder noodzakelijk is om tot de optimale temperatuurinstellingen van deze zones te komen. Rekening houdend met deze complicaties kan een aanzienlijke energiereductie worden behaald in de productie van foliën, pijpen en flessen door het voorverwarmen van granulaat.

In hoofdstuk drie zijn de mogelijkheden tot hergebruik van restwarmte voor het voorverwarmen van granulaat onderzocht. De numerieke techniek, zoals gepresenteerd in deel 1, is gebruikt om de geometrie van de luchtinlaat van warme lucht in een silo met granulaat te optimaliseren. Als ontwerpvoorwaarde is gesteld dat de conditie van het granulaat in de silo een zogenaamd 'incipient' bed dient te zijn in plaats van een volledig 'fluidized' bed. Vervolgens is een opstelling gebouwd, waarmee de numerieke simulaties zijn gevalideerd. De experimenten tonen aan dat de verschillende stadia (packed, incipient en fluidized) van fluïdisatie kunnen worden bereikt onder stabiele condities. Hiermee is aangetoond, dat in het bestaand ontwerp de luchtverdeling in het bed voldoende homogeen is.

In hoofdstuk vier zijn de energetische voordelen van voorverwarming van granulaat aangetoond in een veldtest in een pijp-extrusie-proces. Uit dit onderzoek blijkt, door het gebruik van restwarmte, dat 10% energiebesparing kan worden gerealiseerd in dit proces.
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.

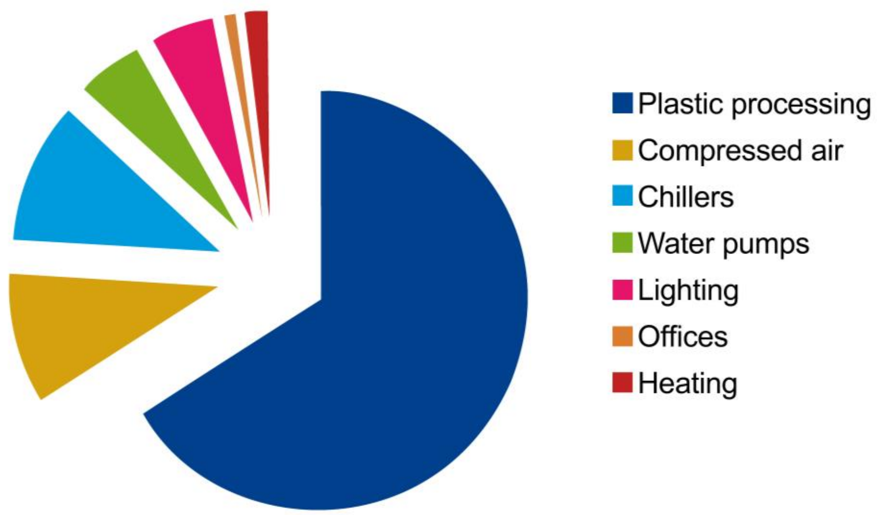

Figure 1.1: Approximate energy cost distribution for plastics processing, taken from [I] with permission from R. Kent

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.

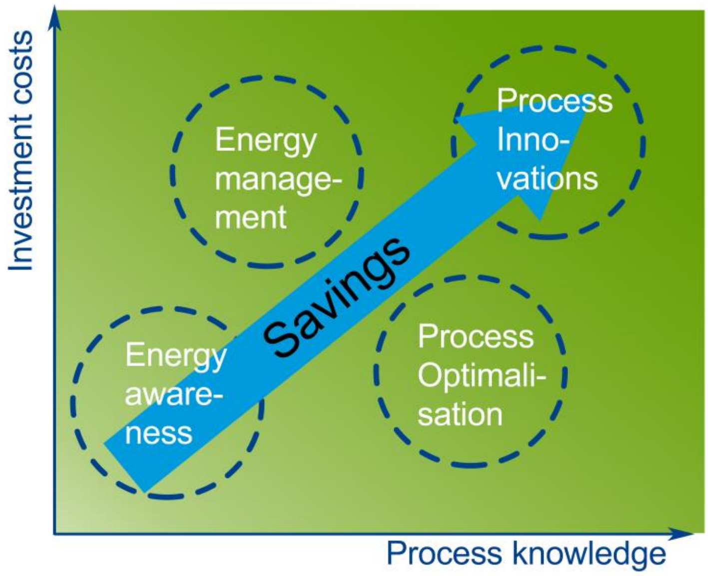

Figure 1.2: Stages in energy policy

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.

In chapter two the tools for awareness, management and optimization are used to define interesting possibilities for process innovations. In the third chapter, a method to use residual heat for preheating granulates is investigated, which has been applied in the production of a pipe extrusion company in chapter four.

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.

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2 Optimization of production processes

Kool, O and Bervoets, L

This chapter focuses on the sheet- and blowmoulding industries, in which energy use is an important factor. Three representative companies were selected. All three companies showed room for improvement, some involving completely new concepts and some using proven concepts from other industrial areas such as the process industry or power generation. The latter options are addressed in this chapter with new, plastic industry related concepts as the subject of the remaining sections of this report. Also, a classification in the stages presented in figure 1.2 is given for the subject treated in each section.

Nomenclature

n = exponent of the expansion/compression
T_1 = Initial temperature (K)
p_1 = the initial pressure (Pa)
w_t = the specific work (J/kg)
R = specific gas constant (J/kgK)
T_2 = final temperature (K)
p_1^* = the initial pressure with EARS (Pa)
w_t^* = the specific work with EARS (J/kg)

2.1 ENERGY MANAGEMENT IN BLOW-MOLDING

The process of creating ‘energy awareness’ in a blow-molding company is described in section 2.1.1 using the NRG-scope. Based on the results of the evaluation of all energy consuming processes in the company, re-use of compressed air was recommended. An example of ‘energy management’ is described in section 2.1.2. Energy saving can be obtained by applying proven technology from other industrial areas for the energy losses in the usage of compressed air.

2.1.1 THE NRG-SCOPE

The NRG-scope[1] is a tool to map the total energy use of a company and to monitor the total energy performance of an individual company. The analysis also yields the basic information required for the identification of energy optimization measures. The scope generates performance indicators such as the energy use per kg product, but it also produces the Windesheim Efficiency Energy Index (WEEI). This indicator allows companies with different manufacturing techniques to compare energy use for the same final product.

[1] Unfortunately, the NRG-scope is only available in Dutch.
[1] www.dumocom.nl

The NRG-scope[1] consists of a questionnaire regarding the actual energy use as well as the abatement measures already implemented. The questions are divided into four sections: Office facilities, Production facilities housing, Process equipment and Management.

It is accompanied by a calculation model (EXCEL), for data entry. The model then generates the relevant performance indicators. The advantage is that data can easily be updated, making it feasible to run the scan periodically.

2.1.1.1 ADDITIONS TO THE ORIGINAL NRG SCOPE

Previously, the scan was performed by a trained Windesheim representative, either a student or an employee. This way, every question was interpreted in more or less the same way at all companies, it required a lot of resources. It can be more efficient to have the entire process performed by employees of the company itself. To make this possible, each question was reformulated such that it can be interpreted in only one way and it requires no -or as little as possible- specialist knowledge. To achieve this, each question was accompanied by a short description.

Another addition to the scan there are some extra questions concerning the ‘green’ management of the company:

“Is the total energy use of your company known and available?”

“Are employees encouraged to think in a ‘sustainable way?”

“Are the responsibilities concerning sustainable energy explicitly assigned to individual employees?”

“Is specified to what extent the company has incorporated sustainability in its management?”

2.1.1.2 APPLICATION OF THE NRG-SCOPE

The impact of energy management in blow-molding processes was determined in a company Dumocom BV in Almelo, the Netherlands. Dumocom is a manufacturer of PET (polyethylene terephthalate) bottles for chemicals, foodstuff, cosmetics, detergents and pharmaceutical products. Dumocom focuses on excellence of quality, (food) safety, flexibility, service and reliability.

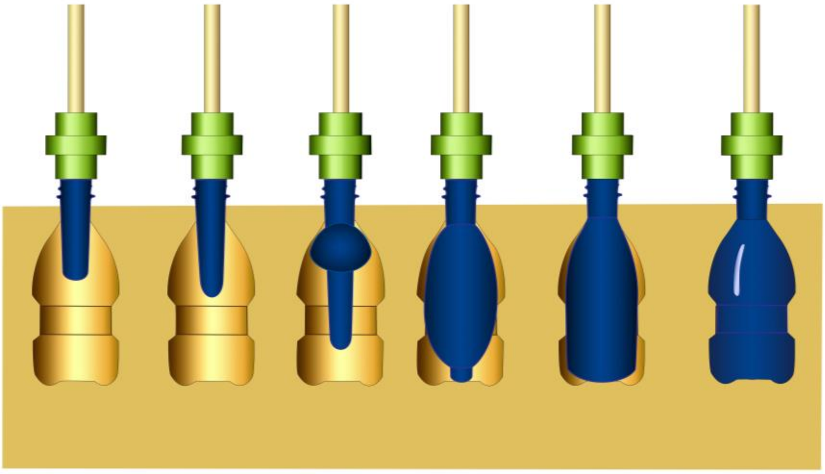

Figure 2.1: Blow molding of PET bottles

The basic principle of the production of PET bottles is shown in figure 2.1. The process starts with a preform, shaped like a test tube. The preforms are manufactured on site during a separate molding process. A preform is pushed into a bottle-shaped mould, is reheated, elongated with a stretch rod and simultaneously blown into the mould with compressed air. This combined expansion process produces a bottle of higher strength and stiffness than other manufacturing methods.

Completion of the scope within Dumocom led to a lower (= less favorable) WEEI score than expected beforehand (32%). A closer inspection within the company led to several recommendations:

Reduction of ‘idle-time’ of various machinery: a number of machines were not switched off when running idle. For example, when the blowing-machine was running idle, leakage of compressed air was audible. The conveyer belt kept on running, along with several auxiliary systems. This results in considerable energy use.

Replacement of conventional TL-lighting with LED-TL lighting: LED-TL lighting leads to a reduction in energy consumption of over 50%. The ROI of this investment is estimated to be 2-3 years, not taking into account installation costs.

Other recommendations included:

- Correct installation and set-up of motion sensors,
- Investigate reuse of compressed air, as described below, and make an inventory of all process machinery with respect to energy consumption.

2.1.2 RECYCLING OF COMPRESSED AIR

In the production process of PET bottles (blow-molding), see figure 2.1, compressed air supplies the force needed to push the stretch rod into the preform and for the pressurization of the preform in the mold. Compression of sufficient air requires large compressors with high energy consumption. After the molding process, the freshly shaped bottles are decompressed; the air is released to the environment by air valves, which causes a lot of energy loss and a high noise level.

2.1.2.1 EXHAUSTED AIR RECYCLING SYSTEM

To reclaim the energy losses a system was invented and patented by the name of 'EARS' (Exhausted Air Recycling System) [1], claiming energy reductions up to 20-40%. In the current project the system was introduced to the production site of Dumocom. This project was carried out in close cooperation with EARS Netherlands BV , (Haaksbergen), and FHT Compressed Air BV , located in Deurne. FHT supplies total solutions for pneumatics and compressed air.

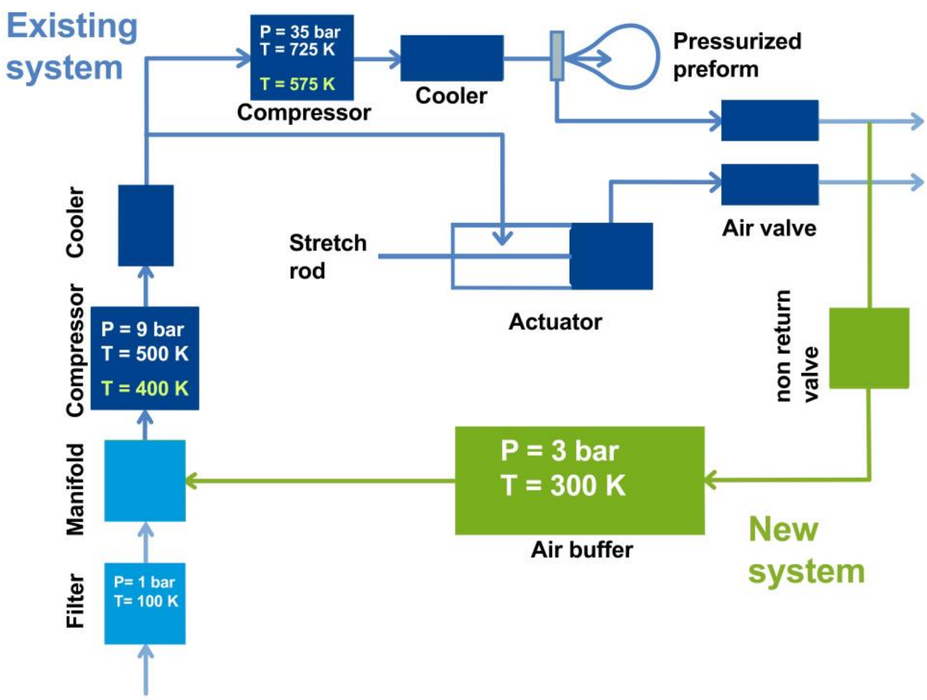

Figure 2.2: the blow molding production process

[1] www.earsnederland.nl
[1] www.fhtperslucht.nl

The basic principle of a blow molding production process with the EARS system is schematically shown in figure 2.2. In normal operation, the air is sucked in at ambient conditions (pressure equals 1 bar and temperature equals 293 K) from the environment. Since the inlet air might be contaminated and rather dusty it has to be cleaned by a filter system. The compressed air system at Dumocom is divided into an 8-9 bar low pressure circuit and a 35 bar high pressure circuit. Due to the compression the air will rise in temperature till 725 K, so it has to be cooled before it can be used for the stretch rod actuators and the pressurization of the preform. When the molding process is completed, the air will be released to the environment by an air valve. This system is controlled by the demand of air from the production process.

In the EARS system the exhaust air from the process is fed back to the compressor at a higher pressure than the ambient conditions by a specially designed and patented manifold. To minimize pressure fluctuations, an air buffer of sufficient capacity is installed; a check valve prevents unwanted air flow back into the process. If 100% of the compressed air were recycled, the system could be fully operated with recycled air. However, some leakage in the system will always occur and additional air from the environment is needed. An important requirement for using the EARS system is the use of frequency controlled compressors.

The benefits of the system are: a reduction of compressor power, cooling capacity and noise as well as an increase in the cycle time of the filter system.

2.1.2.2 EXEMPLARY CALCULATIONS

The work per kg of an ideal gas (unit: J/kg), during an ideal compression cycle, can be calculated using the following formula [2].

$$w_t = \frac{-n}{n-1} R T_1 \left(\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1 \right) \qquad (2.1)$$

w_t= specific work (J/kg), n =exponent of the expansion/compression, R =specific gas constant (J/kgK), T_1 =initial temperature (K), p_1= initial pressure (Pa), p_2= final pressure (Pa).

To calculate the energy savings the ratio of the specific work at different initial pressures is important. This ratio can be calculated from the previous formula;

$$\frac{w_t^*}{w_t} = \frac{\left(\left(\frac{p_2}{p_1^*}\right)^{\frac{n-1}{n}} - 1 \right)}{\left(\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1 \right)} \qquad (2.2)$$

Where p_1^* is the initial pressure with EARS, p_1 is the initial pressure without EARS, w_t^* is the specific work with EARS and w_t is the specific work without EARS.

Using the following values: n=1.32, p_1=1 bar, p_2=8 bar, p_1^*=3 bar, the ratio $\frac{w_t^*}{w_t}$ equals 0.41, resulting in 59% savings. In this case it is assumed that no external air (at environmental pressure) needs to be supplied once the system is started up, and that the efficiency of all other components is not modified.

The real savings will be lower, because external air will have to be added, efficiencies will change and the compression cycle won't be an ideal cycle as assumed in these formulas. However, this result can be used as a first approximation.

Cooling capacity: The temperature of the compressed air is easily calculated for an ideal gas by Poisson's law;

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \qquad (2.3)$$

The compression ratio in the EARS system is lower than in the existing system and consequently, so is the temperature after compression. The temperature after compression is 500 K upon compression from atmospheric conditions. For recompression of recycled air with a pressure of 3 bar it is approximately 400 K. In a high pressure circuit the temperature is reduced from 725 K to 575 K. This means less cooling is required which also saves energy.

2.1.2.3 FURTHER REMARKS

The air in a production environment is contaminated with for example, dust, soot, pollen and vapour (oil and water). To ensure a long lifetime for pneumatic components, the air has to be cleaned by a series of filters and dryers to remove these contaminations. By recycling clean compressed air these cleaners can be downsized and have longer maintenance intervals.

On the other hand, pneumatic tools are known to be very noisy. The air vented off to the environment produces so much noise that people have to wear hearing protection in the production hall. Using the EARS system, the air circulates in a closed system, which reduces noise levels.

Although the basic principles are simple and the benefits obvious, the system has a potentially negative influence on the working of actuators, particularly those which function depends severely on timing. An example of such an actuator is the stretch rod actuator, as described in section 2.1.2.1.

These effects have to be examined in practice to assess their influence on the product quality.

2.1.3 SUMMARIZING

The improvements of the energy-scan method have potentially led to a scan that's easier to use by individual companies. A possible next step would be to make the scan accessible in a web-based environment. Application of the scan at Dumocom led to a lower WEEI score than expected. This encouraged the company to investigate possible sources of energy saving.

One of the examples of saving energy by good energy management is the application of a proven technology to reclaim the energy losses in the use of compressed air. Although the technology was successfully applied in other industrial areas, adaptions had to be made to the system of compressed air. The effect on the blow molding process had to be investigated with respect to the response time of actuators. This demonstrates the intersection between the processes of 'energy management' and 'process innovation' from figure 1.2.

2.2 PROCESS OPTIMIZATION IN FILM EXTRUSION

A third stage in defining an energy saving plan is 'process optimization'. This stage will be demonstrated by film extrusion processes, see figure 2.3, and the study was carried out at Sphere Nederland BV[5] situated in Hardenberg. The company produces, amongst others, biodegradable garbage bags based on potato starch. Innovation is very important to Sphere to reduce the impact of their activities on the environment. Firstly, the energy use of various types of extruders was analyzed, in order to find out where most energy is consumed [b]. Secondly, the temperature of different zones in the extruder and of the granules was examined to minimize the energy use [c].

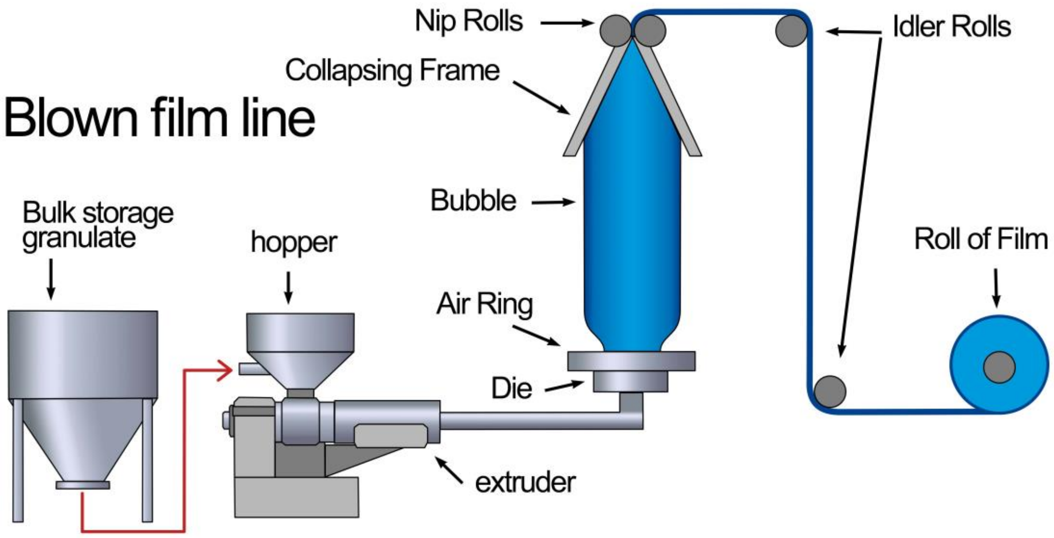

Figure 2.3: Blown film line

[5] www.sphere-nederland.nl

2.2.1 ENGERGY USE BY DIFFERENT TYPES OF EXTRUDERS

The energy consumption of two extrusion lines (“1” and “17”) was determined by measuring the usage of five different energy consumers of these lines during half an hour of operation. These were: the granule transport compressor (A), the electric motor for the screw (B), electric heating of the ‘oven’[6] (C), electric heating of the extruder head (D) and the fans for film cooling (E), see figure 2.4. Please mind that the compressor for the bulk transport, blending and weighing are not taken into account.

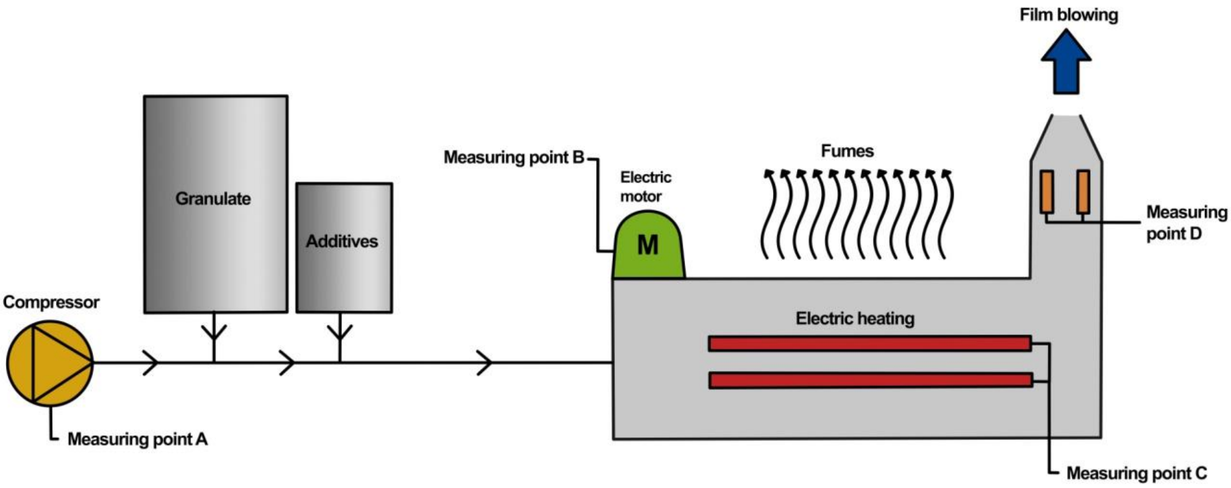

Figure 2.4: Energy consumers in a Blown film line

The extrusion lines are different with respect to the type of motors for the screws, the type of fans for the cooling and the possibilities to measure the energy use of the oven and the extruder head separately.

Extruder 1 has frequency controlled, asynchronous electro motors, three direct current ventilators and a separate measurement on the extrusion head.

Extruder 17 has direct current electro motors, two frequency controlled fans and combined measurement tools for heating.

[6] Section after the screw where the granulate is heated by electric heating

When comparing the results it has to be noted, that there are slight differences in throughput for both machines and also the processed material, both recycled PE, is from a different source. The measurements are summarized in table 2.1.

Table 2.1: Energy use of extruder lines

		Extruder 1	Extruder 17
Throughput	kg/h	203	212
Electric motor (B)	MWh	363	412*
Heating (C and D)	MWh	75	27*
Cooling (E)	MWh	75	37*
Compressor (A)	MWh	94	90*
Total	**MWh**	**607**	**566***

* values corrected for small difference in throughput

The energy consumption is largest for the electric motors. The energy consumption of the frequency controlled motor of extruder 1 is substantially lower. On the other hand, the energy usage of the frequency controlled fans for cooling of extruder 17 is much less than for extruder 1.

The compressor for transport of granules also contributes substantially to the energy consumption of this extrusion process. Since the energy consumption fluctuates considerably during the process, it is recommended to repeat these measurements over a longer period of time. Ideally such measurements should be made when both lines are running under comparable conditions of throughput, material and temperatures.

2.2.2 ENGERGY USE BY DIFFERENT TYPES OF EXTRUDERS

In the previous section it was mentioned, that heating and cooling are two of the parameters in the process with respect to energy use. The main power consumption for heating and melting in the extruder is given by shear friction of the screw, supported by additional heating by electrical elements. To allow accurate control of the temperature of the melt, the heating section is divided into several zones. Some zones are also equipped with cooling to prevent overheating of the melt. This process is schematically represented in figure 2.5 with 8 heating zones. In the second, third and fourth zone additional cooling can be applied. Each zone has an individual temperature set point. The activity of each zone can be controlled automatically to achieve the local temperature settings.

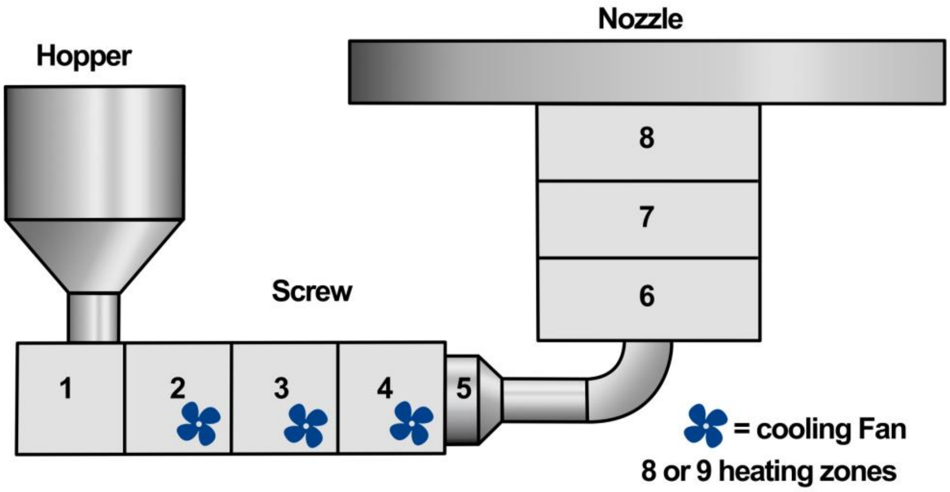

Figure 2.5: Schematic setup of measurements

The percentages of the activity of each zone were monitored. The heating elements of the various zones have different maximum power consumption, meaning the energy consumption per zone cannot directly be inferred from the percentages.

The temperature and activity settings selected by the operator were registered on different days. Two days are presented in figures 2.6 and 2.7. The blue line –mostly coinciding with the red line- represents the set point of the temperature, the red line the actual temperature value.

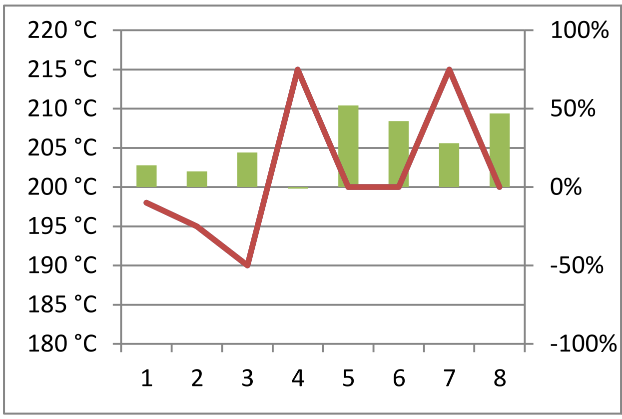

Figure 2.6: power consumption (5,4 kW) on 9-4-2013

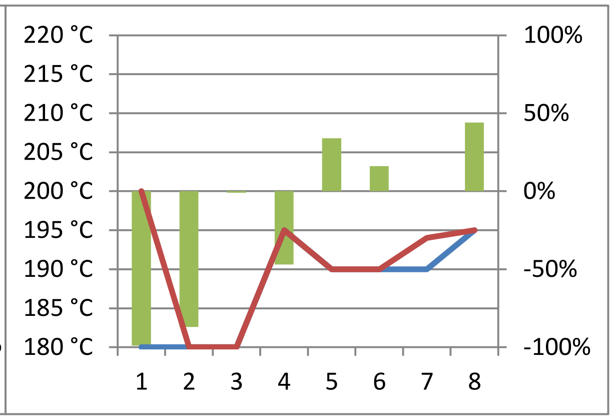

Figure 2.7: power consumption (4,5 kW) on 7-5-2013

The green bars represent the percentage of the maximum heating or cooling that was applied at each zone. Negative bars mean cooling and positive bars mean heating. In figure 2.6 the red line and the blue line coincide, meaning the set temperatures are all complied with. Since the red line and the blue line in figure 2.7 do not coincide it can be concluded that there is not enough cooling for zone 1, 7 and 8 because of the absence of a cooling element in these zones. It can be observed from the graphs that the settings on both days are very different. The set point for the temperature was considerably lower on the 7th of May with respect to the 9th of April for unclear reasons. When checked with the operators, it was found that settings can be changed as a result of malfunction in the process (i.e. bursting/tearing of the film), because of changes in the supply of base-products or because of atmospheric conditions (temperature, humidity). The exact rheological behavior of the material in the screw is hardly known to the operators. The ambient temperature was not measured on these two days, which can have a considerable effect on the energy consumption, see figure 2.11.

On the 26th of March 2013, the temperature settings were changed with respect to the settings of the operator, figure 2.8a. First, the temperatures were set to the maximum temperature of 220 °C, figure 2.8b and secondly to a minimum temperature of 180 °C, figure 2.8c.

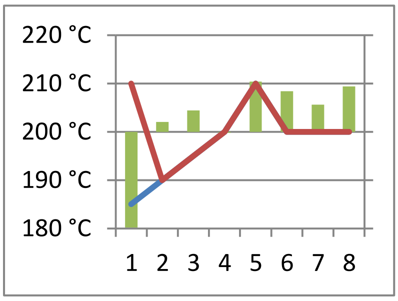

Figure 2.8a: original settings (energy costs (€3.77) (EH €0,62; EM €3.14)

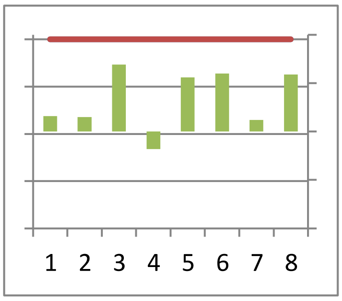

Figure 2.8b: temperature 220 °C (energy costs (€3.72) (EH €0,90; EM €2.82)

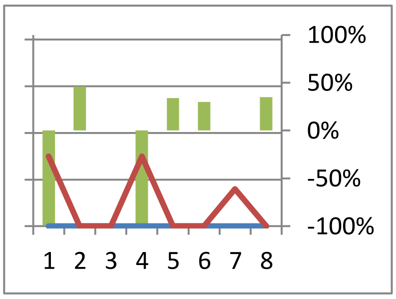

Figure 2.8c: temperature 180 °C (energy costs (€3.63) (EH €0,48; EM €3.15)

Since the temperature settings influence the power needed to drive the screw, the electric motor has to be monitored to judge energy savings. EH represents the costs per hour for electric heating and EM represents the cost per hour for the electric motor. It was found that both the high setting (220 °C) delivered energy saving as well as the lowest setting (180 °C). The high settings require more energy for the electric heating and less energy for the electric motor. The low settings lead to more viscous dissipation of screw and thereby the energy needed for the electric motor is higher. From these figure is can be concluded that to reach optimized settings both energy consumptions have to be minimized.

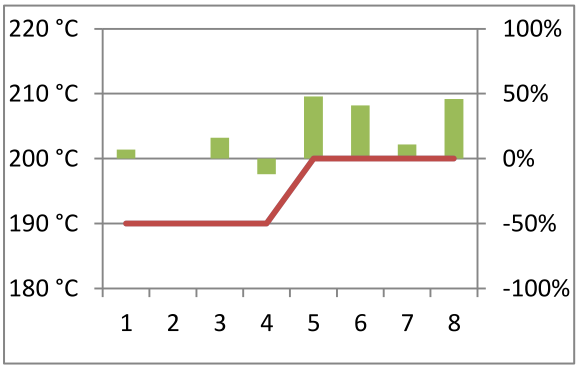

Figure 2.9a: original settings, energy costs (€2.72) (EH €0,51; EM €2.21)

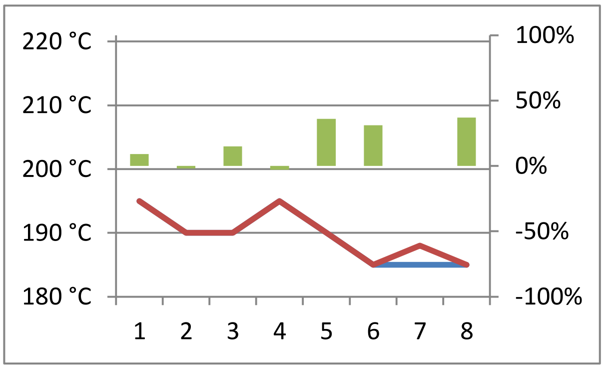

Figure 2.9b: optimized settings, energy costs (€2.56) (EH €0,39; EM €2.18)

In an experiment on the 16th of May 2013 optimized settings with respect to energy use are applied trying to minimize both the energy for the electric heating as well as the energy for the electric motor. In figures 2.9a and 2.9b the original setting and the optimized setting are shown. In figure 2.9b it can also be seen, that the optimized settings are obtained by avoiding cooling of a zone. The energy savings are about 6% for the optimized settings with respect to the original settings.

Obviously, the experiments have to be carried out in a way that the product quality stays within the specifications. To determine the influence on the quality of the film, mechanical tests were performed to measure strength and elasticity as well as a drop test. Small differences, within the specifications, were found. The vertical strength and elasticity of the high-temperature product were found to be greater than the product with the constant low setting. On the other hand, the horizontal strength was higher in the product with low temperature settings. The experiments were repeated on two other machines with similar results.

Finally, the effect of ambient temperature on energy consumption was monitored during the test period. The ambient temperature is presented in figure 2.10. and the energy consumption is presented in figure 2.11. From these pictures can be concluded that € 0,30 per hour per machine can be saved with a temperature increase of 20 °C, which means an annual saving of about €50.000 for the total production capacity of Sphere.

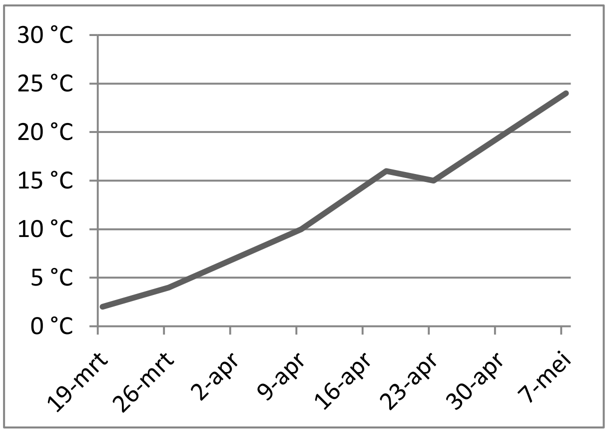

Figure 2.10: Outside temperature (max per day)

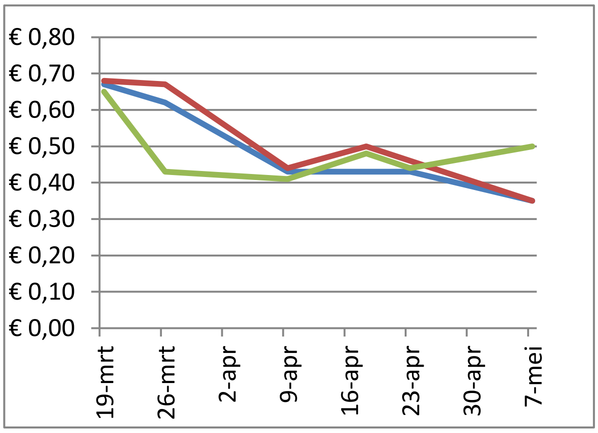

Figure 2.11: energy costs per machine per hour
Blue: machine 7, Green: machine 14
and red: machine 8

From these results, it can be concluded that pre-heating of granules by residual heat from other processes will lead to substantial energy and costs savings, which will be studied in section 2.3 and chapters 3 and 4.

2.2.3 SUMMARIZING

The conclusions for the possibilities of energy savings at the production facilities of Sphere are:

- The positive effect on energy savings using frequency controlled devices for electric motors, heating and cooling fans was clearly demonstrated;
- ‘Tweaking’ the temperature settings of a film blowing machine quickly reduces the power consumption with 6% or more, without a noticeable decrease in film quality. This can only be performed when operators are provided with correct information concerning total electric energy consumption, and this information is, preferably, logged and reviewed on a regular basis.
- Preheating of granules can contribute to a substantial saving in costs and environmental impact.

The stage of ‘energy optimisation’ in the energy saving plan is clearly demonstrated in this section. A sound knowledge of the processes is needed to find the optimum settings for the temperatures in the different zones of an extruder. On the other hand hardly any investments in equipment are needed in order to reduce energy costs with several per cent.

2.3 RESIDUAL HEAT IN SHEET MOLDING PROCESSES

The possibilities of re-use of residual heat from several processes in sheet molding were investigated at BPI Indupac BV[7] (Hardenberg). Indupac produces industrial bags and consumer packaging by way of 3 layer co-extrusion. The company has extensive printing facilities consisting of CI 6-8 colour printing presses to print the customer information on the packaging. Residual heat is produced by the cooling of the film (60-70 °C), by the drying of the ink in the printing process (130 °C) and by combustion of the vapour of ink solvents submitted by the printing process (800 °C). The objective is to find ways to use this residual heat in low temperature applications such as space heating and preheating of granules. For that study the behaviour of granular flow in the storage for daily stock was investigated and the contamination of the air with pollutant had to be analysed. Although little knowledge of the actual production (sheet molding) is needed for this research, the work will be considered as ‘process optimisation’.

2.3.1 BRIDGE FORMATION IN GRANULAR FLOW

An important design rule in applying residual heat to preheat granules is to prevent bridge formation in granular flow. These bridges are formed due to cohesive forces between the granular particles, which depend on [d]:

- The material properties, like molecular weight, of the granules;
- The particle size and distribution. Fine powder shows stronger cohesive behaviour than granules;
- The pressure acting on the formed bridges;
- The humidity. Van der Waals forces result in increased bridge formation when humidity increases;
- The temperature, the granules become softer and more adhesive at higher temperature, which promotes bridge formation;
- The dimensions of channels, orifices, etc. When the size of the passages is in the order of a few times the particle diameters, flow will be restricted.

The production process at BPI is schematically represented in figure 2.12. The granules are supplied to the extruder by force of gravity from the day storage container. The granular flow through an orifice was investigated in [e] based on the Beverloo law [2], [3]. This law relates the granular mass flow to the required residence time and the level of the granules in the container, the length and width of the container, the packing fraction and the density of the granules. The applicability of this law depends on the fulfillment of a set of conditions to create a smooth flow [2] such as the material height relative to the width of the container and the width of the container compared to the size of an orifice. The preferred diameter of piping can be determined to allow a smooth flow throughout the silo’s and to prevent blockage. This study [e] shows that with respect to the transport of granules in production processes, several design criteria and physical phenomena have to be taken into account.

[7] www.indupac.com

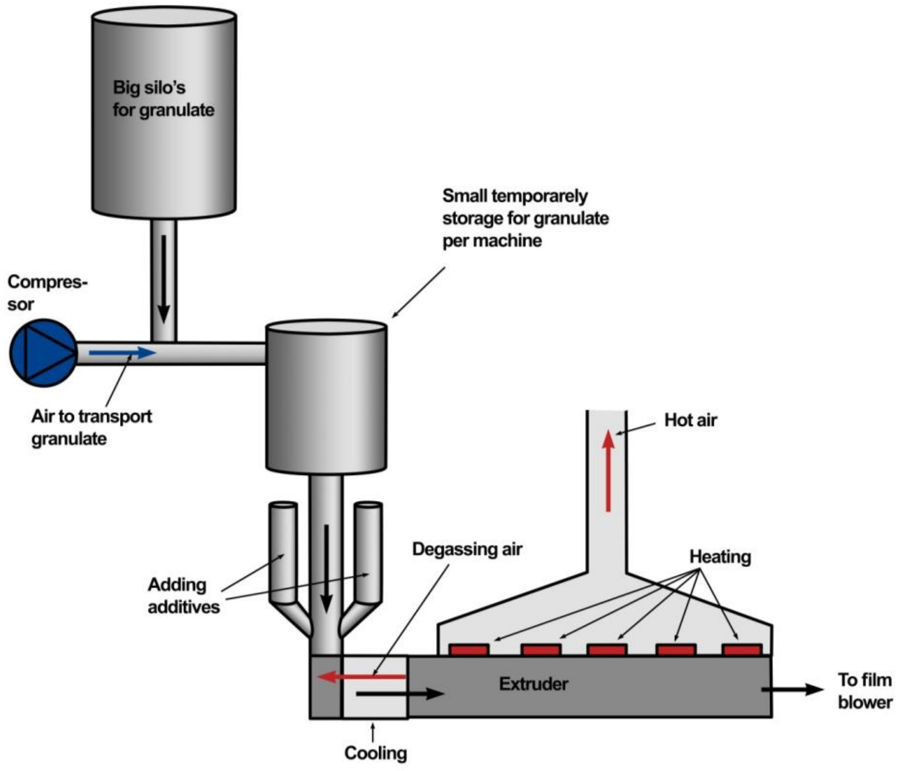

Figure 2.12: Schematic setup of production process

Another important factor is the release of hot gasses from the melting of the granules inside the extruder. The temperature can rise as high as the melting temperature of the material, for example to 125 °C for polyethylene, or even higher. These gasses can only be released in the direction opposed to the granule flow due to the pressure buildup in the extruder. Since the residence time of the granules in the extruder is short, the granules will only heat up at the surface. This will cause the granules to stick to each other and the formation of bridges is obvious. To avoid blockage, the gasses are cooled to 40 °C directly in the inlet of the extruder (see fig. 2.12). From this it can be concluded, that preheating close to the inlet does not make any sense.

Furthermore to make preheating in the extruder sensible, it was also investigated to release the hot gasses in the direction of the heating zone of the extruder [f]. This is only possible with adaptions to the screw as well as to the extruder. However, due to the low heat conductivity of plastics, the contact time in the extruder is too short in order to heat up the core of the granules homogeneously. From this can be concluded, that preheating of the granules is only feasible in the containers for the daily storage of granules, where the residence time is long enough to heat the granules to the core.

In order to decide which energy flow is most suited for preheating the granules in the day storage, the target temperature had to be specified. To avoid the risk of bridge formation, it is recommended to heat the granules made of polyethylene to a temperature not higher than 50 °C. Therefore a heat flow of moderate temperature (i.e. <100 °C) is preferable. This makes the residual heat from the film cooling the most plausible candidate. Unfortunately, this air stream is contaminated with paraffin waxes which might affect the product quality. Roughly, there are two ways to solve this possible loss of quality. First based on the percentage of waxes in the granules, the product quality can be examined with respect to the specification. Secondly, the waxes can be filtered out in order to supply clean air to the granulate flow. This last option is examined in section 2.3.2.

2.3.2 CONTAMINATION BY PARAFFIN WAX

In the context of re-using energy in production processes, hot air is one of the heat sources that currently are 'lost'. For example, in production processes where plastics are processed by film blowing (see Figure 2.3), a lot of air is heated during film cooling or drying of printing ink. In these two processes mentioned above, ambient air is warmed to 60 and 140 ˚C respectively. In the current manufacturing process of BPI, all this hot air is discharged into the atmosphere, which constitutes a considerable loss of heat. A process like foil printing emits 850.000 kWh/year of heat [g].

Of course it would considerably reduce the energy demand of the company if this waste heat could be reclaimed. A major drawback to using waste air is that it is usually contaminated. As a result, the possibilities to use this hot air elsewhere are limited.

This project investigates the possibility to remove the pollutants in the hot air to make it possible to apply the energy in the hot air elsewhere for instance in direct heating of an industrial unit or pre-heating of granules. As mentioned, warm exhaust air is usually polluted. Major pollutants that may appear are acids, ozone, alcohols and paraffins [g], especially in the case if polyolefin processing.

The pollution appears in the liquid phase as tiny droplets (mist) and in the vapor phase dissolved in the air. The concentration of the fog is measured by filtering the air with a PVC filter for a specified time. The weight of the pollution was determined with infrared (FT-IR, NIOSH 5026). The concentration of the mist was measured in 2013 and was in the order of 5200 µg/m^3. The composition of the vapor pollution was measured by capturing the vapor in an activated carbon filter. The pollution was released from the filter and measured by a gas chromatography - mass spectrometer (GC-MS) method. The total amount of vapor was about 15.000 µg/m^3 and mostly consists of light hydrocarbons (C6–C12) and alcohols [h].

In this study we will focus on eliminating paraffins, since the mist will cause most problems by precipitating in the upstream piping and the granular bed. First of all the properties of paraffin were investigated and to determine in what forms paraffins occur. Next, the existing possibilities to filter Paraffin vapors and droplets from air were investigated. Based on the collected knowledge, the most promising technique was studied to determine whether and if so, how well the filter works.

Paraffin

The film-blowing process of polyolefin releases certain molecules, collectively known as *paraffins*. The general chemical formula for paraffin is $CH3(CH2)_nCH3$, where the number of n can vary between 16-57. Figure 1 and 2 show examples of straight and branched versions.

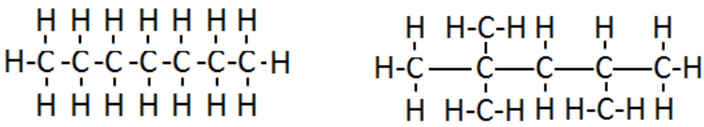

Figure 2.13: An example of linear paraffine (left) and branched paraffine (right)

These paraffins appear mostly in the liquid phase as droplets in the air stream as can be seen in the measurement reports. Hardly any heavy hydrocarbons are found in the vapor phase.

Properties

Paraffins are hydrophobic. They aren't soluble in water or alcohol, but they can be dissolved in carbon tetrachloride, benzene, petrol and ether. Important properties like melting point, viscosity and vapor pressure are dependent on the chemical composition of the specific paraffin. For example, the vapor pressure of paraffins was studied in [4]. The dependence of vapor pressure on temperature causes the formation of more liquid droplets by reducing the temperature of the air.

Possible filter techniques

There are many ways to remove impurities from air [g], dependent on the appearance of the pollution (vapor of mist). Two of the best known techniques are cloth filtering and electrostatic filtering. In this project, both methods were investigated and assessed for their suitability to remove paraffin from waste air.

In a cloth filter, polluted air flows through a package of cloth, the fibers of which retain most of the impurities while the air passes through more or less unimpeded. Cloth filters have a high cleaning capacity, but, dependent on the nature of the pollutants they require frequent cleaning.

At BPI Indupac a test-setup was installed using this principle. After two weeks, however, it already needed to be replaced. This short interval is considered to be a disadvantage. Another disadvantage of this filtering method is that not all types of fumes are absorbed by the cloth.
Because this filtering method proved to be insufficient, the second method (using electrostatic charge) was investigated. Electrostatic filtering is created by electrostatically charging the impurities, then using an electric field to pull them out of the air stream.

The company of United Air Specialists, Inc. was requested to propose a solution. The method UAS uses consists of two combined filters (see fig 2.14). The pre-filter cleans the air of large dust particles, after which the remaining impurities are electrostatically charged by the ionizer and pulled out of the airstream by the collector. The collector is an aluminum precipitator, which needs to be cleaned every few weeks, depending on the intensity of use. This cleaning process is mostly automated.

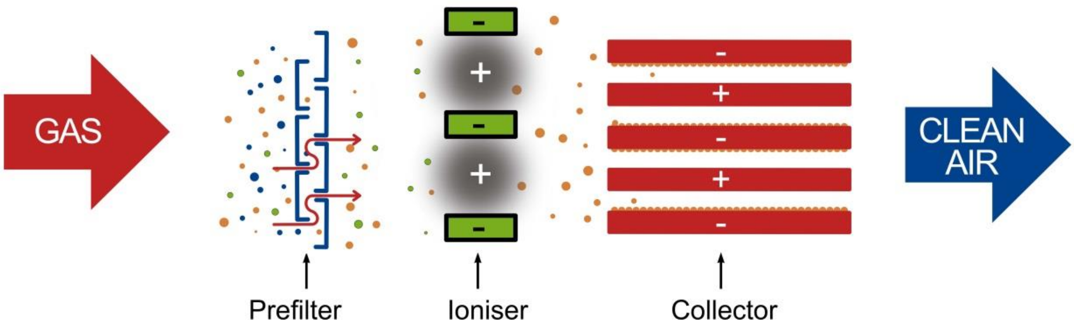

Figure 2.14: Schematic representation of electrostatic filtering (source: UAS, Inc.)

The company claims an effectivity of 97%. If the exhaust air isn't clean enough, the process can be repeated.

In a trial performed at BPI Indupac [h] in 2014, the concentration of oil droplets was reduced from 5200 µg/m^3 to 710 µg/m^3, a reduction of 86%. The concentration of the oil droplets was measured using the same technique as in 2013. Also, the composition of the vapor was measured. These measurements show no reduction of the vapor content of the pollution, which is understandable for the used method. Only droplets can be charged in the air stream. To reduce the vapor content the temperature of the air should be reduced drastically. Further investigation needs to be performed in order to know if this percentage can be improved on even more. The composition of the air before and after the electrostatic filter has to be measured and also the composition and amount of drained liquid from the filter.

2.3.3 EFFICIENT USE OF WASTE HEAT AND COLD

BPI Indupac has the facility to print customer-specified texts and graphics on their products with the aid of printing inks based on volatile solvents, mostly alcohols. The prints are dried in a 130 °C air flow. The air is refreshed by an exhaust ventilation system. Under Dutch environmental legislation, the solvent content of the exhaust air is too high to allow a free discharge into the atmosphere. To counter this, the solvents are oxidized catalytically in a combustion unit integrated into the exhaust system. The air flow is fed through two combustion chambers (figure 2.15), each containing a packing of ceramic catalyst plates.

Like most oxidation processes, catalytic combustion is exothermal. This means the catalyst chambers heat up considerably during the passage of the air. In order for the process to work, the catalyst temperature should not exceed 850 °C. Too high a temperature will damage the equipment; too low a temperature will slow down the process and harm the exhaust air quality. A sensible system of temperature control is therefore required.

In the present system, this is obtained by periodically inverting the air flow. The flow direction is controlled by the Ecotherm valve shown in figure 2.15.

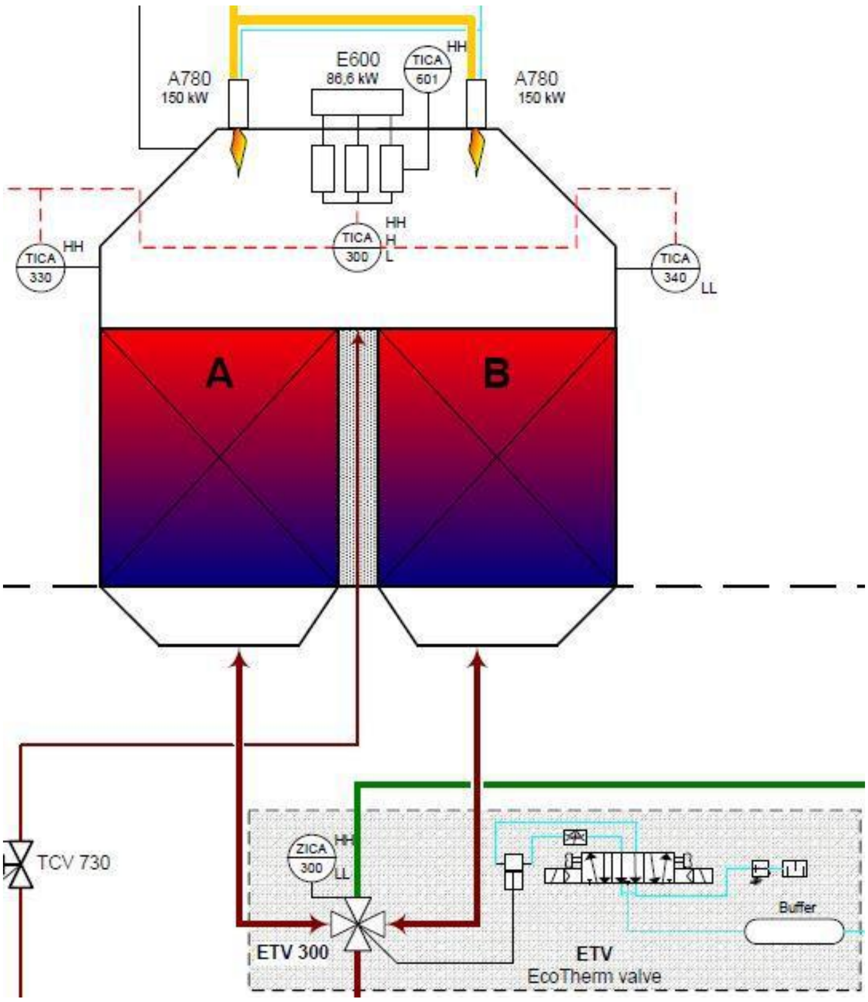

Figure 2.15: A diagram of the catalytic combustor.
The Ecotherm valve (ETV) periodically inverts the air flow through the system

A natural gas burner is used to start-up the unit and to maintain the correct temperature during periods of low exhaust air flow.

The air-born solvents represent considerable energy content. Typically, the unit generates about 815.000 kWh/year of thermal energy, the equivalent of 92.700 m3/year of natural gas. This equals around 30 % of the annual gas consumption at the site. In terms of natural gas, the solvent energy content represents an annual value of € 37.000. Enough reason therefore, to investigate the possibility to reclaim this heat. However to use this heat, for example for preheating of granules, heating the heat zones of an extruder or heating of the building, the temperature has to be adjusted to the desired level for the process.

The most feasible solution to reclaim the heat and adjust the temperature proved to be the plate heat exchanger, this option combining high efficiency, low maintenance cost, constructional simplicity, low maintenance and reasonable investments. Since heat exchangers for the relevant temperature range are not standard equipment, the decision was made to design a custom built heat exchanger (fig. 2.16)

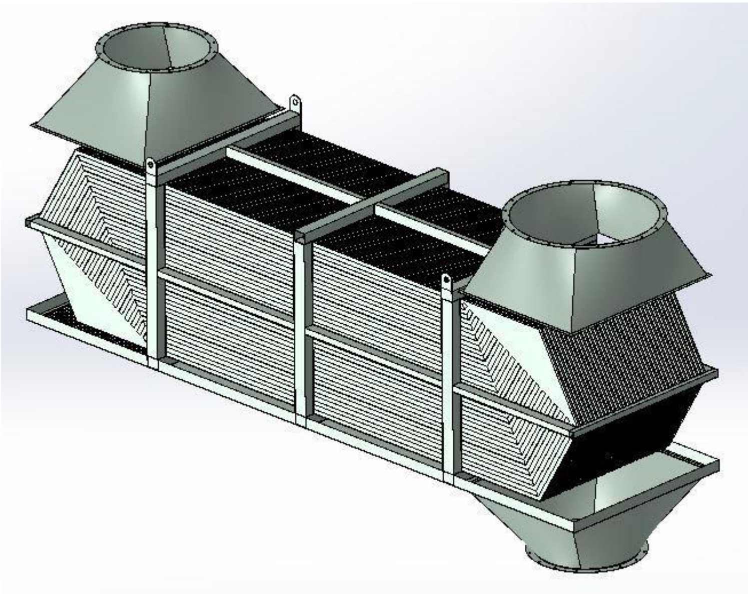

Figure 2.16 A design for a cross-flow heat exchanger.

As shown in figure 2.17, the heat exchanger is built up out of corrugated metal sheets, welded together.

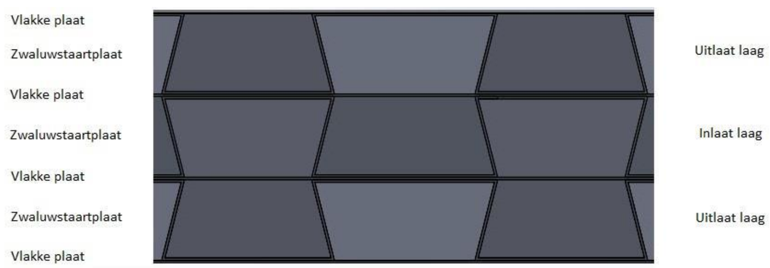

Figure 2.17: A cross section of the plate heat exchanger.

A model study of the unit demonstrated that the heat exchanger potentially reduces the site energy demand by about 800.000 kWh/year. This number is slightly lower than the generated thermal energy, because of heat loss in the heat exchanger.

A further study addressed the cooling demand of the site. The sheet material is cooled in two stages: by a 14 °C air flow positioned immediately behind the extruder head and by water cooled rollers in the calendar downstream. In the current situation the extruder head cooling is supplied by forced cooling of ventilation air taken from the production hall. The project demonstrated that it is technically feasible to use outside air directly, since ambient air temperatures are well below the required minimum of 14 °C during more than eight months per annum. In fact, during most of the year, ambient air has to be heated to prevent the sheet from being cooled too fast.

The project resulted in the design of an air preheater, which utilizes warm exhaust air to heat ambient air to the desired temperature levels, essentially by a carefully controlled mixing process. The mixer is shown in figure 2.18. As is the case in many industrial processes where free cooling is viable, this leads to very substantial savings in electric energy. .

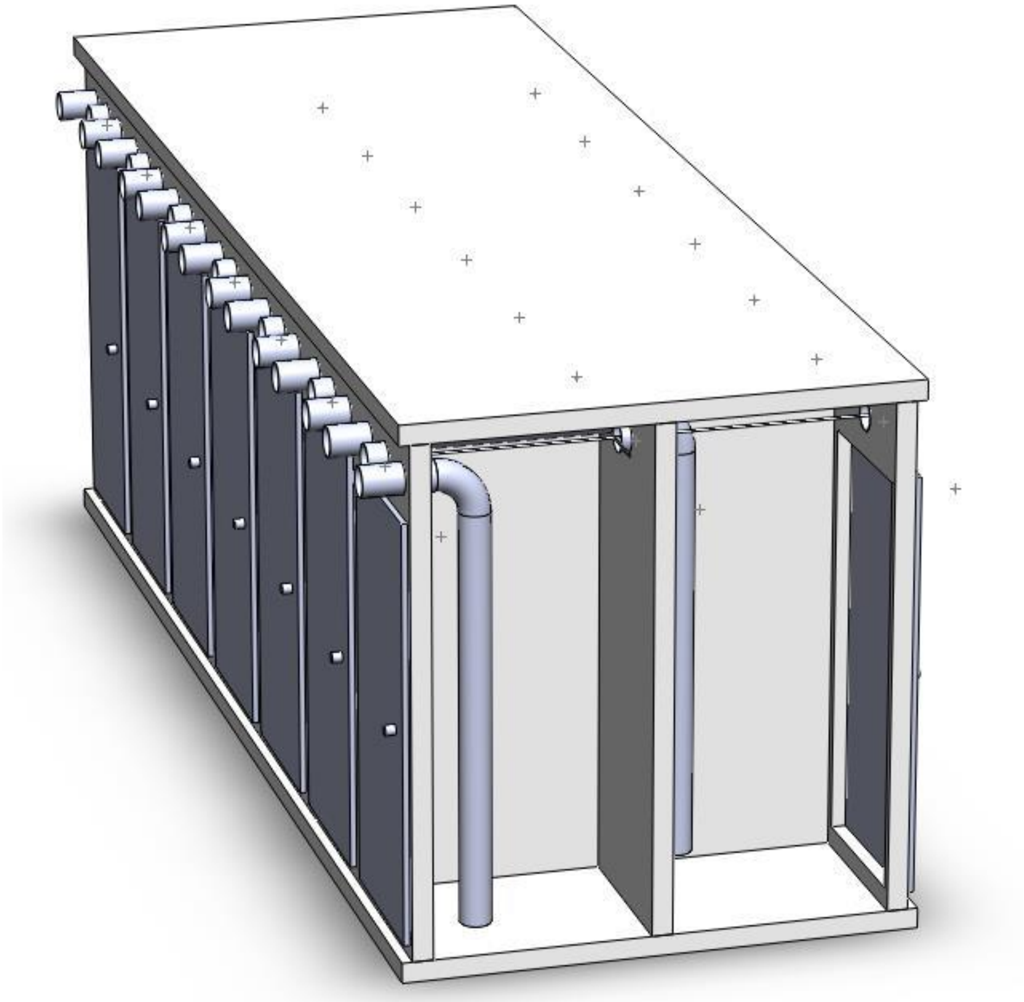

Figure 2.18: The air mixer

2.3.4 SUMMARIZING

Both the temperature (and flow) of the source heat and the location where the granules are heated have to be considered carefully to prevent bridge formation when granules are pre-heated,

To make waste heat more widely useable, filtering the air of paraffins can be necessary. Therefore, the option of electrostatic filtering was investigated.

Reclaiming the heat that was generated in a combustion unit, using a plate heat-exchanger, can lead to substantial savings.

2.4 CONCLUSIONS

In this chapter several examples of the stages in figure 2.1 are demonstrated. Analysis of the processes in the ‘energy awareness’ and ‘energy management’ can lead to interesting opportunities for energy savings. For some opportunities existing equipment can optimized by tweaking the settings, in other challenges proven technology from other industrial areas can be adapted to the specific plastic process and in other cases process innovation is needed, see chapter 3 and 4.

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3. Re-use and storage of energy

Buist, J., Bervoets, L., and Hummel, C.

In paragraph 2.3 the possibility to use residual heat to preheat granules in extrusion processes has been discussed. The benefits and limitations of using preheating in a blow molding process have been examined briefly. The most important limitation, with respect to the amount of energy that can be reused, is the maximum temperature of air blown through the bed of granules. When the temperature is too high, bridge formation can occur due to coherence of the granules. Also the dimensions of the tunnel play an important role. The flow of granules will be restricted when the dimensions of channels, openings, etc. are in the order of magnitude of a few particle diameters.

In order to obtain an evenly distributed temperature profile throughout the bed of granules, the air flow distribution in the particle bed needs to be examined. Figure 3.1 gives a schematic view of an experimental setup as suggested by SHS, see chapter 4. The inflow of hot air is realised with a downer. Similar constructions are published in the case of preheating granules for effective drying, see [1].

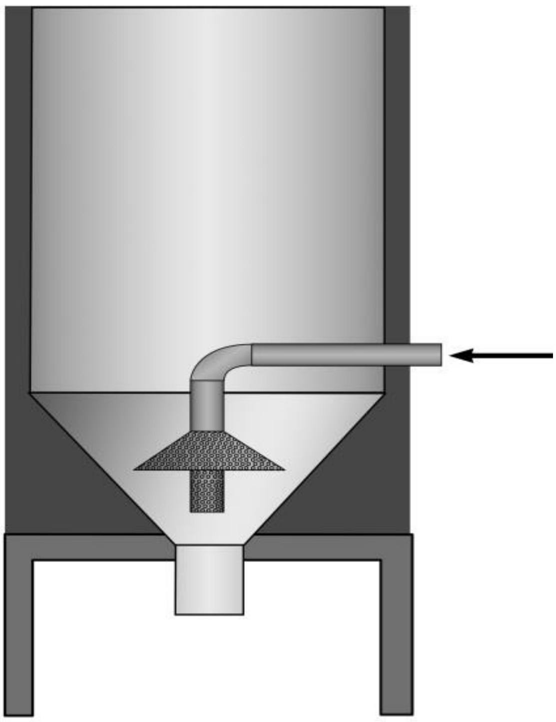

Figure 3.1: Granulate bunker

The question is: Is this type of inflow the optimal way to obtain an even temperature distribution, with a gradually increasing temperature profile towards the outlet of the bunker?

In this chapter, the flow distribution in the channel will be examined by computational fluid dynamics (see [a] for the basic ideas of CFD) in order to optimize the temperature distribution. Furthermore, the theoretical background of fluidized beds is outlined. The numerical calculations are presented and discussed. The design of a test facility to validate the CFD calculations is presented.

Nomenclature

u_o = superficial velocity	m/s	p = pressure drop	Pa
d_p = particle size	m	L = length of the bed	m
ρ_f = density of the fluid	kg/m^3	ρ_p = density of the particles	kg/m^3
μ = viscosity	Pa.s	ε = void fraction	-
φ = spherisity	-	g = gravitational constant	m/s^2
Δ = difference	-	Q_m = mass flow	kg/s
D_0 = diameter of the orifice	m	d_g = diameter of the granules	m
C = discharge coefficient	-	k = shape coefficient	-

3.1 THEORETICAL BACKGROUND

Fluidized beds are often used to optimize the heat transfer in chemical reactors. The rate of heat transfer from air to particles will increase with more fluidization in the bed. According to [2], different stages in fluidized beds can be distinguished, depending on the flow rate:

- Packed or fixed bed: At low flow rates the air flows through the void spaces between the stationary particles. The particles will remain in place and slightly vibrate around their position.
- Incipient bed: At higher flow rates the particles are suspended in the flow of air. The viscous force of the flow, acting on the particles in upwards direction, is just in balance with the gravitational forces. In this stage, the bed is just fluidized. The superficial velocity of the air can be calculated using the above mentioned balance in viscous force and gravity force. This superficial velocity is known as the minimum fluidization velocity.
- Fluidized bed: In case of a gas-solid system, the flow rate will be beyond the minimum fluidization velocity. Large instabilities of the flow will occur with bubbling and channelling of gas. At even higher flow rates, the gas bubbles will coalesce and grow. These large bubbles will rise to form a slug flow and the particles will recirculate in the bed. This situation is highly undesirable with respect to the requirement of a gradually increase in temperature in downwards direction.

In an incipient bed the temperature gradient can be controlled by a well distributed and uniform gas flow. Based on the optimized heat exchange and the controllable temperature gradients in the bed, an incipient bed is preferred for preheating granules. The objective of this study is to develop and to validate a numerical method to design the air inlet chamber and to predict the flow distribution in incipient beds.

Before presenting the numerical method, the characteristics of incipient beds with respect to pressure drop and bed height have been examined analytically. Based on this examination the superficial velocity can be calculated.

The pressure drop and bed height are given in figure 3.2 as a function of the superficial velocity, see [3].

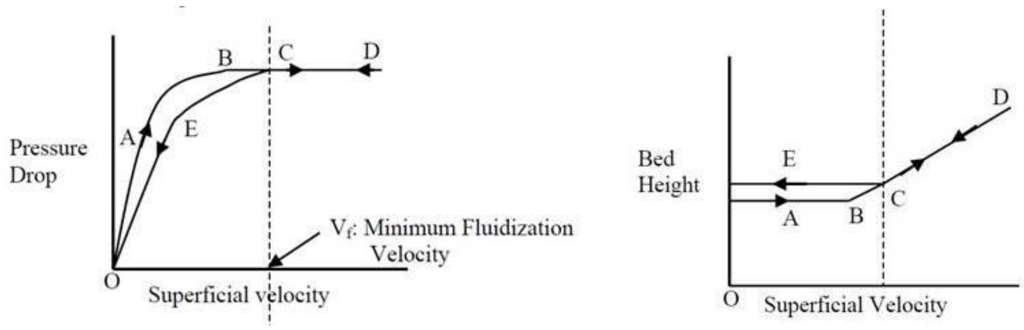

Figure 3.2: Pressure drop and bed height against superficial velocity

With increasing superficial velocity the pressure drop will increase, until a minimum fluidization velocity has been reached. At that stage, the bed is considered as fully fluidized and the pressure drop stays constant when the velocity is increased further.

The pressure drop per meter in a particle bed is given by Ergun's equation [4]:

$$\frac{\Delta p}{L} = \frac{150\mu(1-\varepsilon)^2}{\varphi^2\varepsilon^3 d_p^2} \times u_0 + \frac{1.75(1-\varepsilon)\rho_f}{\varphi\varepsilon^3 d_p} \times u_0^2 \qquad (3.1)$$

The pressure drop in this equation is determined by the viscous force of the gas flow acting on the particles. The pressure drop is a function, amongst others, of the superficial velocity.

The gravity force acting on the particles is given by equation (3.2). The difference in density is determined by the different densities of granules and air.

$$\Delta p = \Delta\rho g L(1-\varepsilon) \qquad (3.2)$$

Equation (3.1) can be made dimensionless by multiplying both sides by the following factor:

$$\frac{\rho_f d_p^3}{\mu^2(1-\varepsilon)} \qquad (3.3)$$

Substitution of the pressure drop due to gravity into Ergun's equation and multiplying by the above factor gives for the left-hand side of equation (3.1) the Archimedes number (Ar):

$$Ar = \frac{g\rho_f\left(\rho_p - \rho_f\right) d_p^3}{\mu^2} \qquad (3.4)$$

The resulting formula defines a dimensionless number, giving the ratio between external gravity forces and internal viscous forces acting on a particle.

Finally, in figure 3.2 the bed height is given as a function of the superficial velocity. For a fixed bed the bed height is constant. In case of an incipient bed, the bed height increases with increasing superficial velocity. The bed height increases further in the fluidized situation and the interface becomes unstable. Remarkably, when the superficial velocity in a fully fluidized bed decreases again, the bed height does not return to its original height, but stays at a higher constant level.

3.2 FLOW DISTRIBUTION IN INCIPIENT BEDS

In section 3.1 it was concluded that an incipient bed is the optimal solution to transfer heat in a particle bed. A homogeneous air flow distribution in the bed is important for a controlled temperature gradient. The air flow has been analysed using computational fluid dynamics, see section 3.2.2.

In order to validate the numerical simulations, a test setup was designed. The design of the test facility is inspired on work by the Technical University of Eindhoven [5]. This setup, see figure 3.3, has been adapted in such a way that a transit of granules in the silo is possible. In this way, the influence of the downward flow of granules on the bed behaviour can be investigated. The air flow and air pressure required to obtain an incipient bed are calculated. Based on these values, a suitable fan has been selected.

The results were checked with CFD calculations and finally the flow behaviour is visualized in the experimental setup.

Figure 3.3: test set-up

3.2.1 EXPERIMENTAL SETUP

The design of the setup is described in [b] and has been developed using a 'methodical design' method. The design consists of a pseudo 2D bunker (width 400 mm, depth 80 mm and height 1500 mm). The front side is made of Perspex, to allow a clear view of the motion of the particles in the bed.

A detailed view of the inlet is given in figure 3.4. A standard solution to supply air through an incipient bed is to place a perforated plate between the bed and a pressurized chamber with air beneath the bed. In that case however, no transit of granules is possible in the silo. Therefore, the perforated plate has been replaced by a number of perforated pipes. The distance between the pipes is chosen to be larger than five particle's diameters to avoid bridge formation.

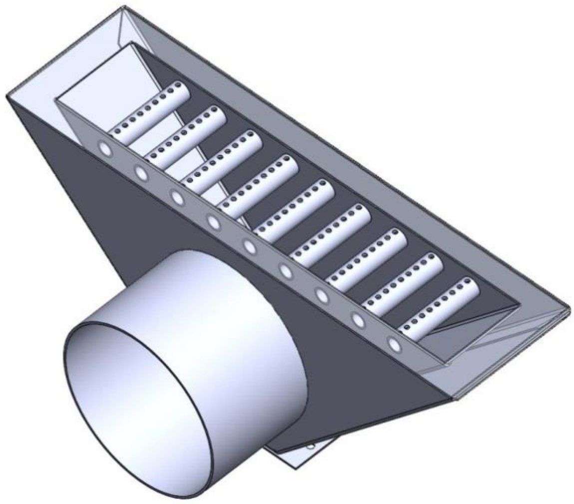

Figure 3.4: Air inlet chamber

The diameter of the holes in the perforation is determined by the requirement that the pressure drop over the inlet is larger than the pressure drop over a fixed bed of granules with a height of 1 m. The number of holes was chosen to permit the creation of enough flow to obtain the minimum fluidization velocity. The pressurized chamber is placed around the bed instead of beneath the bed.

To calculate the pressure drop over the bed of granules, the minimum fluidization velocity is calculated by the balance of viscous forces and gravity forces, combining equation (3.1), (3.2) and (3.3) as:

$$\frac{g\rho_f\left(\rho_p-\rho_f\right)d_p^3}{\mu^2}=\frac{150\mu(1-\varepsilon)}{\varphi^2\varepsilon^3d_p^2}\times u_0+\frac{1.75\rho}{\varphi\varepsilon^3d_p}\times u_0^2 \qquad (3.5)$$

With a particle diameter of 4.4 mm, a particle density of 950 kg/m^3, a sphericity of 0.77 and a packing fraction of 0.6, the minimum fluidization velocity is calculated at 0.88 m/s. With this velocity the pressure drop over the bed of granules can be calculated using equation (3.1) to be 5585 Pa.

In [a] several solutions to extract the granules from the silo are presented, for example by gravity through an orifice or forced by a spindle. The possibilities to use a simple adjustable orifice have been examined in [b], based on the Beverloo law [6] and [7]:

$$Q_m=C\rho\sqrt{g}\left(D_o-kd_g\right)^{5/2} \qquad (3.6)$$

A residence time of 60 minutes is required for the granules to stay in the bed to heat up to the required temperature. The mass flow of granules was calculated dividing the volume of the silo by this residence time times the density of the granules. Calculations based on this theory showed that it was hard to obtain a design of an orifice with controllable flow in this mass flow regime.

Therefore the second option was chosen using a spindle, since the constant rotation dictates the flow of granules. This spindle, see figure 3.5, was produced by rapid manufacturing.

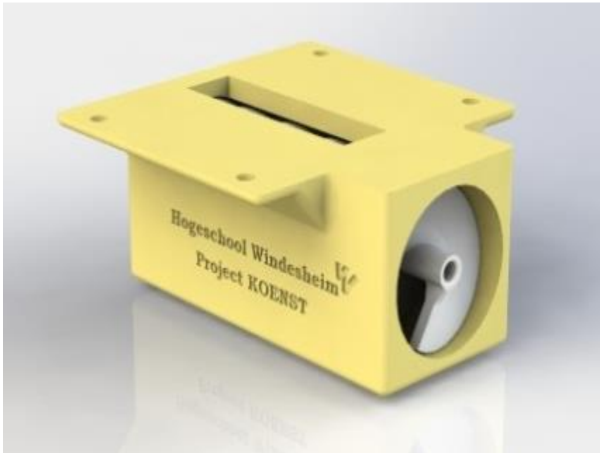

Figure 3.5: Spindle

3.2.2 NUMERICAL CALCULATIONS

The experimental setup, see figure 3.3, was modeled by dividing the flow domain in three subdomains as indicated by different colors, see figure 3.6. The subdomains have different properties. The blue area is the inflow of hot air. The mass flow of air is calculated based on the minimum fluidization velocity, the air density and area of the tunnel. The green area is the outflow of the air at atmospheric pressure.

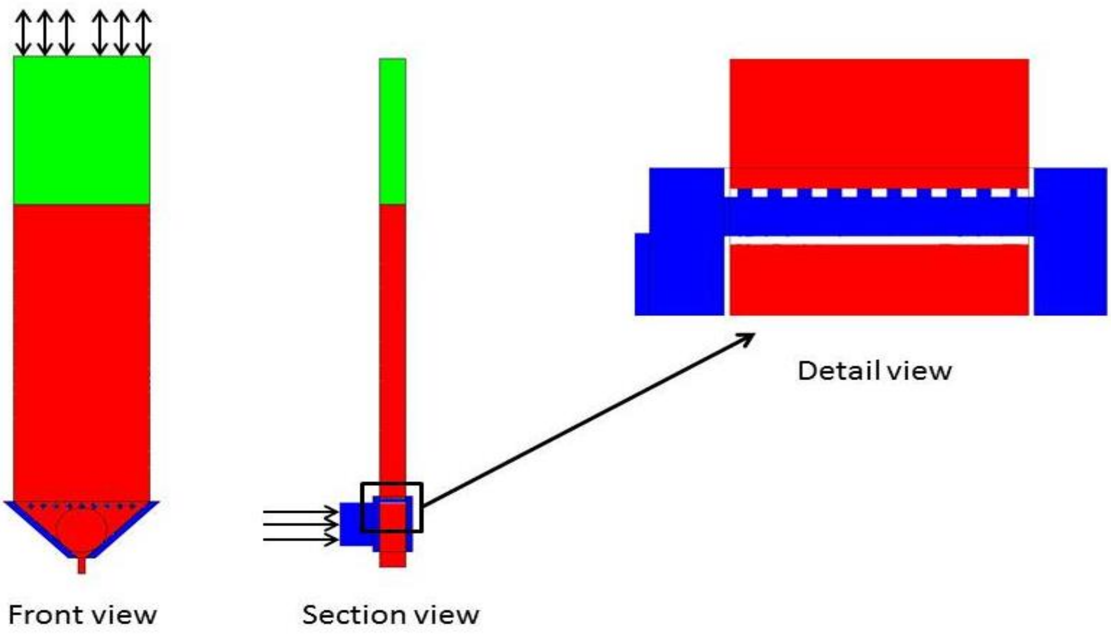

Figure 3.6: Numerical model

In the detailed view the perforation of the pipes is shown. The size of the element in the numerical grid is determined by the requirement that at least five cells in the holes exist. This requirement ensures a reasonable accuracy of the numerical solution. The diameters of the holes in the pipes are in the order of magnitude of the particle size. This means that the minimum grid size for the simulation has to be at least five times smaller than the particle size.

The red domain is the particle bed. For this domain the motion of the granules in the bunker should be calculated with a dispersed solid model. In such a model, a transit of granules in the bunker can be taken into account. However, this model requires that the element size is larger than the particles size of the granules. On the other hand, numerical accuracy demands that the element size in the holes of the perforations is smaller than the diameter of the holes. The perforations in the pipes are smaller than the particles, to prevent particles flowing into the pressurized chamber. Due to these conflicting requirements, it was decided to use a more simplified model for the time being.

In this simplified model, the particle bed is modeled using a porous medium. In this model, the pressure drop and temperature distribution in the bunker are calculated assuming the granules do not move. The minimum fluidization velocity is used to calculate the minimum fluidization flow for the inlet of this model. The porous and fluid medium with different properties is separated by an interface at the position of the perforations in the pipes. At the outlet (in green) there is a fluid domain that consists of air. This fluid domain is also separated from the porous domain by an interface.

The properties for the porous medium are represented by a linear and quadratic contribution in velocity, see equation (3.7). The different resistance coefficients were specified based on the Ergun equation.

$$\frac{\Delta p}{L} = C_{r1} u_0 + C_{r2} u_0^2 \qquad (3.7)$$

Inserting both coefficients (equation 3.8 and 3.9) in equation 3.7 will get the Ergun equation (equation 3.1).

$$C_{r1} = \frac{150 \mu (1-\varepsilon)^2}{\varphi^2 \varepsilon^3 d_p^2} \qquad (3.8)$$

$$C_{r2} = \frac{1.75 \rho_f (1-\varepsilon)}{\varphi \varepsilon^3 d_p} \qquad (3.9)$$

All necessary values for these coefficients to calculate the minimum fluidization velocity are already known, see section 3.2.1. Based on this data, the linear resistance coefficient was calculated at 1320 kg/m^{3}s and the quadratic coefficient as 5700 kg/m^4.

The air velocity profile in the bunker is shown in figure 3.7. The model shows that the velocity is evenly distributed over the porous medium. In the detailed view, the flow distribution just behind the holes in the pipes is shown. The high velocities in the pipes are quickly distributed across the full width of the bed.

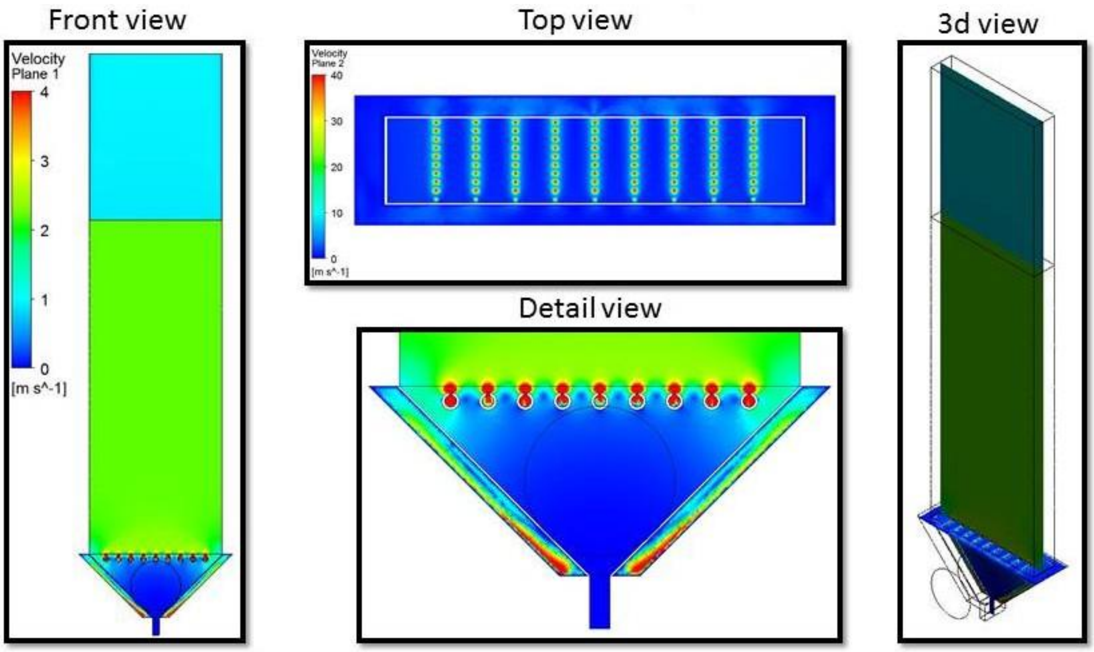

Figure 3.7: Total velocity profile

In the top view, the flow in the perforation is shown. It can be seen that the flow is evenly distributed over the holes in the pipes, which guarantees a good distribution in the depth direction of the bed.

The pressure drop is shown in figure 5.8. The total pressure drop is 11000 Pa. The fan, selected for the experiment, has to deliver this pressure with the flow calculated from the minimum fluidization velocity.

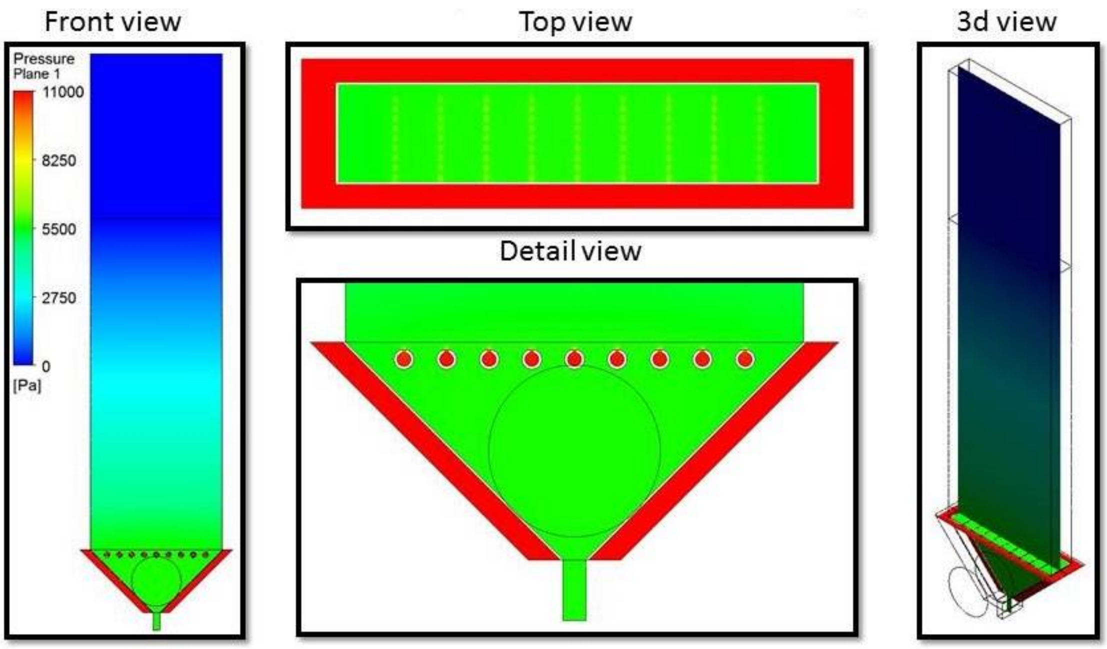

Figure 3.8: Total pressure drop

The pressure drop over the porous medium of one meter is about 5500 Pa, as can be seen by the colors in the legend varying from green to blue. The remaining 5500 Pa pressure drop from the total pressure is created in the pressure chamber. The pressure drop over the fixed bed and the pressure drop over the pressure chamber are almost equal. This indicates that the diameter of the perforations, as described in section 3.2.1, is in line with the requirement to obtain an evenly distributed flow field.

The heat transfer to the HDPE granules can be calculated based on the interfacial area density and the heat transfer coefficient of HDPE. The heat transfer coefficient is an educated guess based on the heat transfer coefficient for PP granules [8]. The thermal conductivity of HDPE and PP is within the same range. The granules have a particle diameter of 0.0044 m. For these particle sizes, an estimate of the thermal conductivity of 50 W/m^2K is a reasonable value.

The interfacial area density is the contact area of a particle with air per particle volume. The maximum possible value for the interfacial area is taken, because in theory particles in an incipient bed do not touch each other. However, in reality this maximum value is almost not feasible.

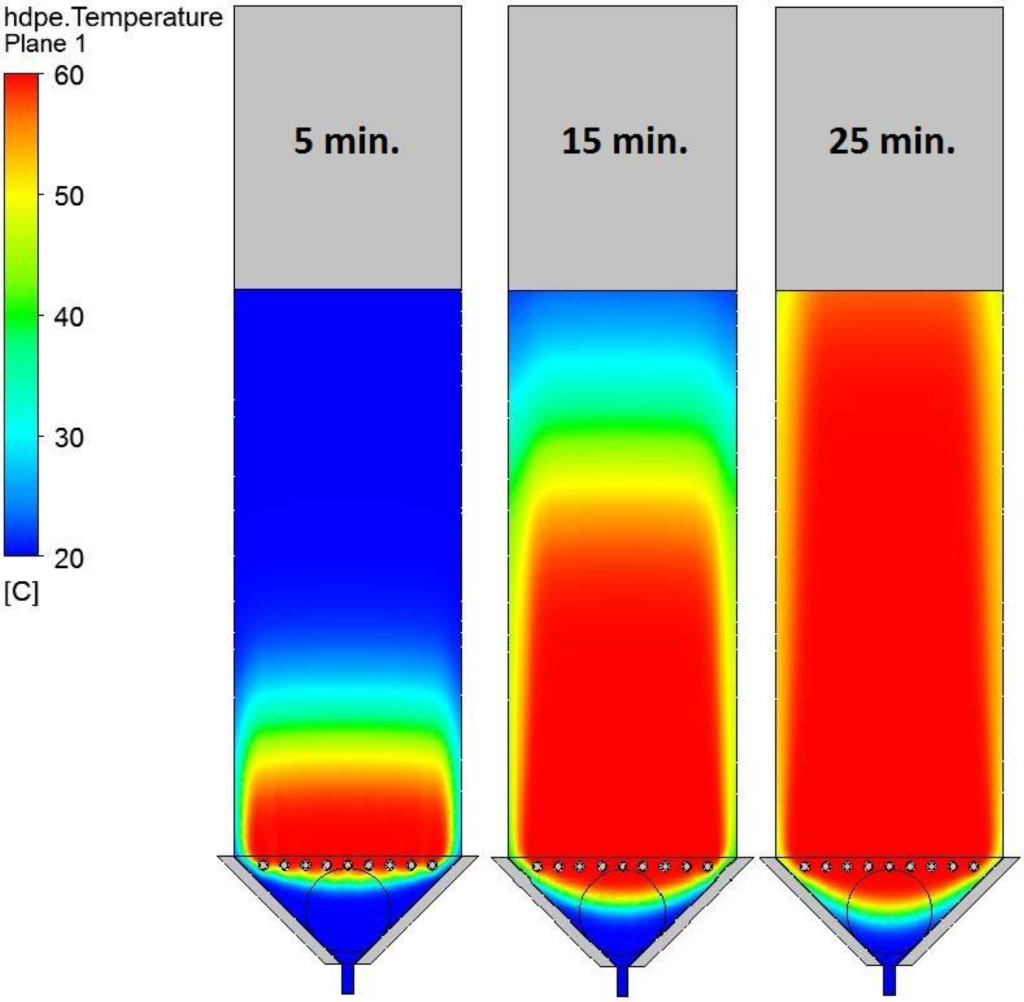

Figure 3.9: Temperature of the granules at different time steps

According to the results in figure 3.9, most of the HDPE reaches the maximum temperature of 60°C after 25 minutes. This is unfeasible in reality, because the maximum value of interfacial area density is taken and adiabatic walls were used in the numerical model. In the lab experiment, the walls are not insulated.

At the bottom of the bunker it is relatively cold, because the heat conductivity is disregarded in this model and no transit of the particles is taken in account.

In fact, the calculation of the heat transfer should have been done with a multiphase model, for example the dispersed solid model. In such models the heat transfer to particles in fixed and fluidized beds for multiphase models can be based on more realistic models, for example Gunn's equation [9]. These heat transfer models are not available for porous media.

3.2.3 EXPERIMENTAL RESULTS

Finally the behavior of fluidized beds was analyzed in an experimental setup. Therefore a suitable fan had to be selected based on the pressure drop calculated with the numerical model. A fan capable of producing a pressure of 11000 Pa at an air flow of 0.028 m^3/s is needed to create a fluidized bed of the granules in this tunnel. In figure 3.10 the different stages of the bed at the test setup are shown.

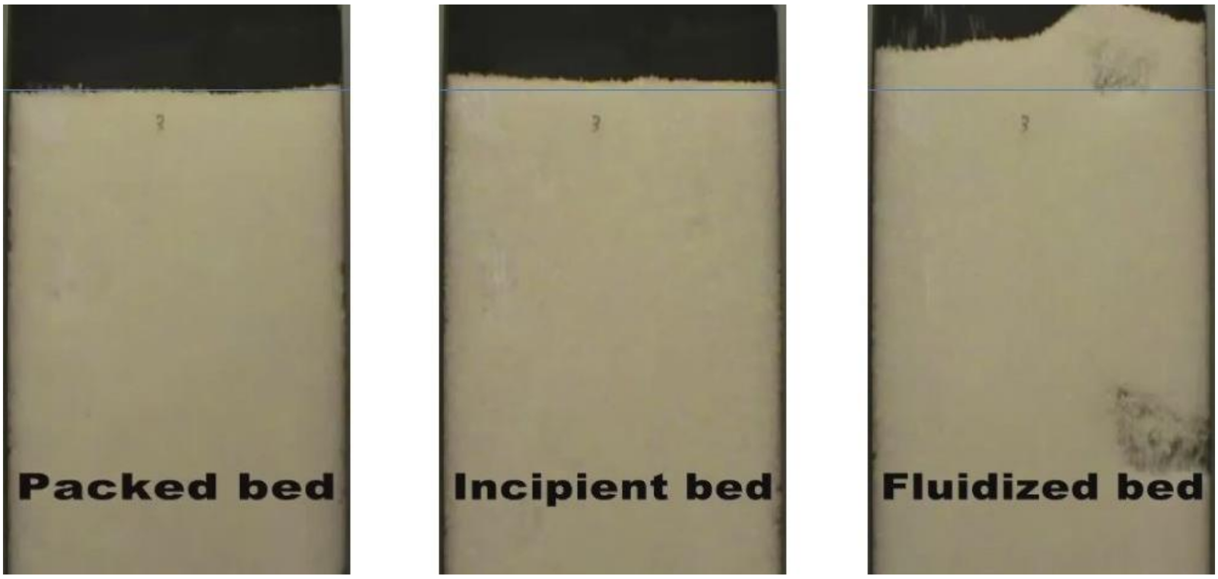

Figure 3.10: Packed, incipient and fluidized bed

First, the packed bed is shown with a stable bed height. The pressure is increasing linearly with increasing velocity. The packed bed changes into an incipient bed when the minimum fluidization velocity is reached. When the state of an incipient bed is reached, the bed height increases slightly because of the minimum amount of air between the granules. When the air velocity rises even more, the bed will fluidize and bubbles of air will flow through the granules just as shown in figure 3.2.

Although the pressure drop and mass flow could not be measured in this setup the observations in changing bed types are according to expectations. Since the transition to an incipient bed occurs almost at the maximum capacity of the fan, it can be concluded that fluidization velocity is predicted correctly. The fluidized state can be achieved with this fan since the pressure drop increases hardly with increasing volume flow.

3.3 CONCLUSIONS

In this study a solid base has been developed to investigate the behaviour of incipient beds to preheat granules in plastic processing. For future improvements the numerical model developed in this study has to be extended to a dispersed solid model. In this model the flow of the particles can be included and a more accurate heat transfer model can be used. Also, the experimental setup can be improved further with respect to insulation, leak tightness, measurement of pressure drop, mass flow and temperatures to obtain even better comparison with the calculations.

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4. Material pre-heating in pipe extrusion process

Spitz, M. and Hiesgen, G.

Plastic processing consumes a lot of electric energy. That fact is valid for all kinds of processing like injection moulding, extrusion, thermoforming and many others. Due to rising energy costs, companies all around Europe are looking for innovative technologies to increase energy efficiency in their production processes.

SHS plus GmbH (Oberhausen, Germany) was founded in 2010 and is specialized in the topic of efficiency of plastics processing. To meet the demand of the market, there are three business areas: Technologies, Software and Consulting.
In the business unit Technologies, among others, SHS is working in the field of development of technologies to improve quality, productivity and energy efficiency of plastics processing production sites. One focus is on the development of devices to use waste heat from the production processes to pre-heat granules before they are processed. The benefit of pre-heating the granules before they are processed is, that the extruder warms them up only from e.g. 80°C up to 220°C instead of 20°C up to 220°C. Usually the temperature difference of 200K is done by the electric drive of the extruder and the heaters of the extruder barrel. If the temperature difference is lower, the result is saved electric energy for the extruder drive. As shown in the following graph, for PE100 (typical plastic pipe material) the theoretic savings are around 20%, if the material is heated up to 80°C before processing.

One question to answer in the context of this project is: What amount of electric energy can be saved in a real production environment.

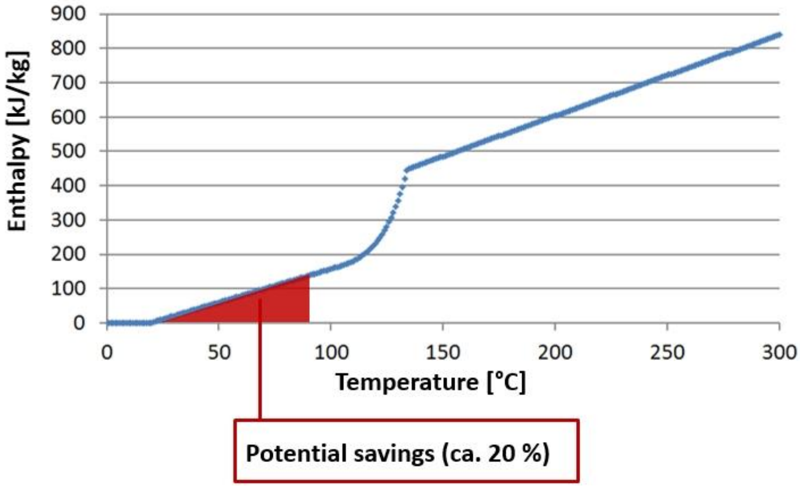

Figure 4.1: Theoretical savings due to pre-heating [3]

4.1 PIPE EXTRUSION PROCESS AND HEAT SOURCES

Previous research work showed, that there is a huge potential for usage of waste heat in the pipe extrusion process [5]. Extrusion is, like many other plastic processing methods, characterized by taking plastic granules at ambient temperature, heat them up using electric energy (rotating a screw), forming a product and cooling the plastic to freeze the geometry of the product. That means, nearly all the heat brought into the plastic before by using electric energy, must be removed to freeze the product geometry. In this project, the focus is on PE100, a typical pipe material that is processed on a temperature level of 220°C. The process is schematically represented in figure 4.2:

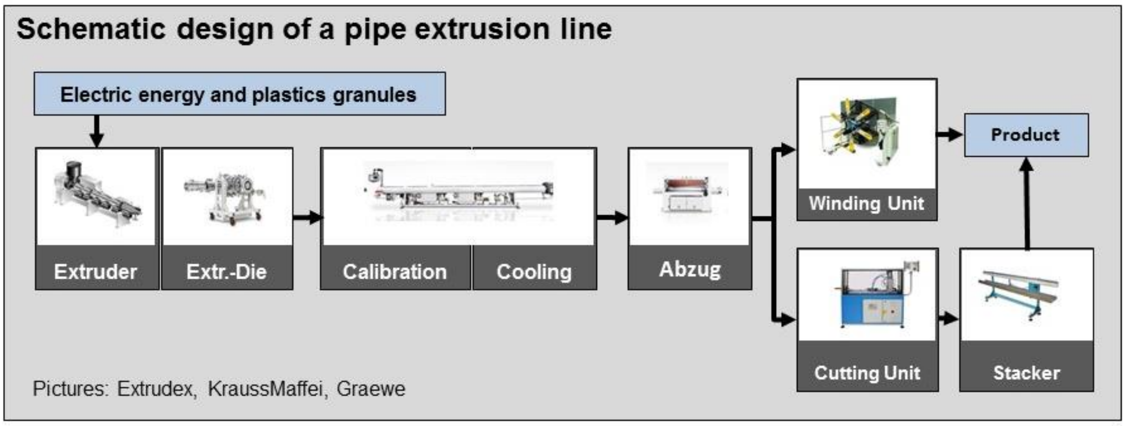

Figure 4.2: Design of a pipe extrusion line

1. The extruder is continuously filled with granules, while a rotating screw heats it up due to dissipation.
2. In the extrusion-die, the pipe geometry is formed
3. The calibration freezes the outer surface of the product to guarantee a good surface and suitable dimensions
4. The cooling section(s) transfer the heat to a cooling medium
5. The pipe is pulled by a caterpillar take-off unit
6. At the end of an extrusion line the pipe can be cut into pieces of a certain length or can be winded

In the process of pipe extrusion are several possibilities to use waste heat and pre-heat the granules. Measurements showed especially two interesting sources that are focused in this project:

1. Waste heat from screw-barrel cooling
2. Waste heat from “inner pipe cooling” [1]

Inner Pipe Cooling is a possibility to suck ambient air through the extruded pipe to cool its inner surface (as shown in figure 4.3). At the extrusion die, the air is leaving at a temperature between 70°C and 150°C having a thermal energy of 5kW to 15kW (and exceeding in some processes).

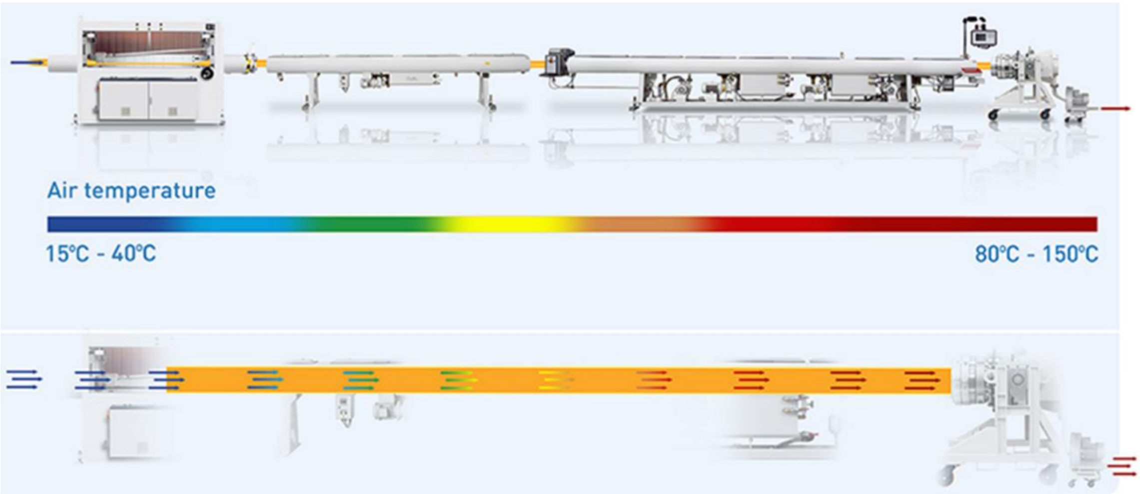

Figure 4.3: Concept of inner pipe cooling [2]

4.2 EXPERIMENTAL SET-UP: EXTRUDER-BARREL COOLING

Today, extruder-barrels are divided into several zones that can be controlled to a certain temperature. In some processes, the zones of the barrel must be cooled by blowers. In other cases the zones are heated by heaters. In case of cooling, a blower, arranged under the barrel cools the zone blowing ambient air along the barrel. The heated air disappears into the production environment at around 100-140°C.
To use the warm air for material pre-heating, the following test set-up is realised:

A suction blower sucks ambient air along three different extruder barrel zones. Valves that are arranged under the cylinder are used to reduce the amount of cooling air to control the temperature of each zone. To avoid a too hot temperature of the air, a bypass-valve can be opened to reduce the air temperature. A maximum of 100°C is defined for the air temperature. That guarantees that the granules don’t get too hot, even if they have a long dwell time inside the pre-heater.

Behind the suction blower, the hot air streams into a pre-heater device (SHS *INGENIO*) where the plastic material is stored, see figure 4.4. The size of the device is 700 liter, enough for 420kg of granules. The material is warmed up by the hot air and then filled into the feed hopper of the extruder. A model of the modified extruder is shown in figure 4.5.

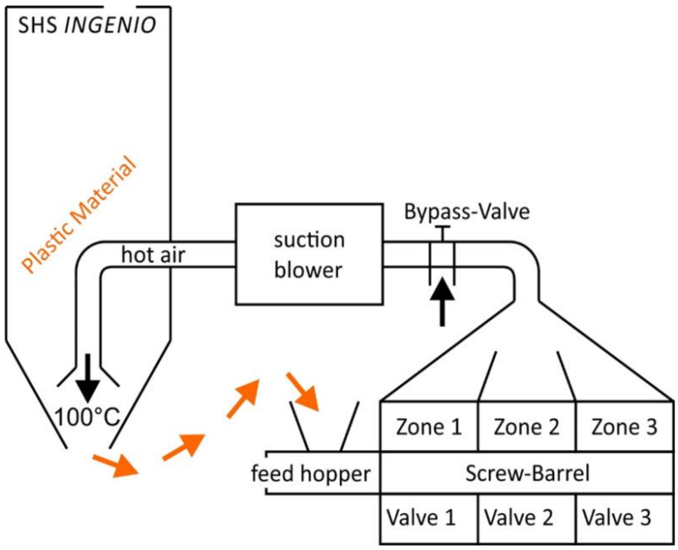

Figure 4.4: Concept of extruder barrel cooling

4.3 EXPERIMENTAL SET-UP: INNER PIPE COOLING.

For this set-up, the heat source is the hot air from the inner pipe cooling during pipe extrusion (see above). Sucking ambient air reverse to extrusion direction through the pipe allows cooling the inner surface of the extruded pipe. Leaving the extrusion die, the air has a temperature of 70°C – 150°C, depending on the dimensions of the pipe and the amount of air.

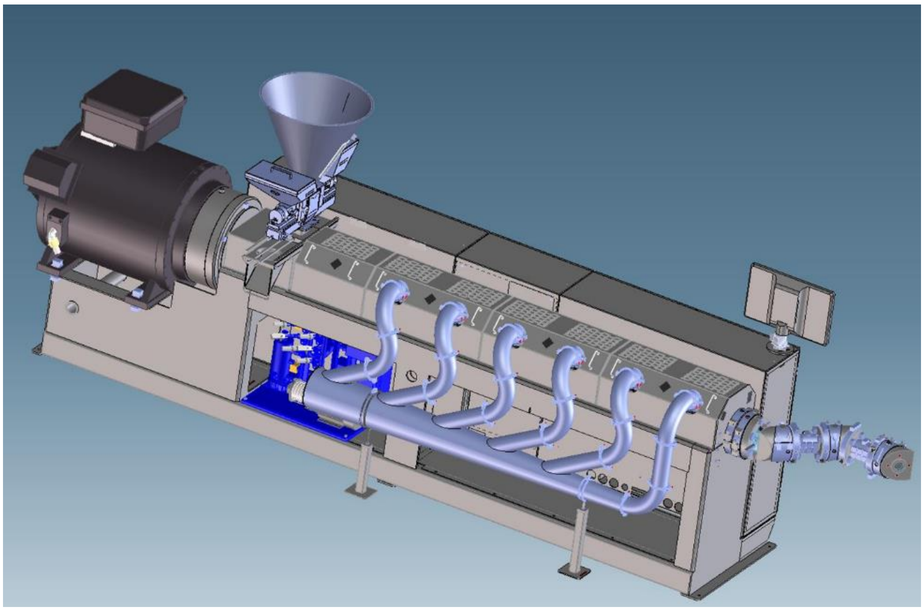

Figure 4.5: model of modified extruder

In many cases, the hot air is polluted with paraffin, which vaporizes inside the pipe. With some materials, that might be a problem, because cooling down the warm air (e.g. using it for material pre-heating) leads to condensing of the paraffin. That fact has to be taken into account in the test set-up, which is shown in figure 4.6.

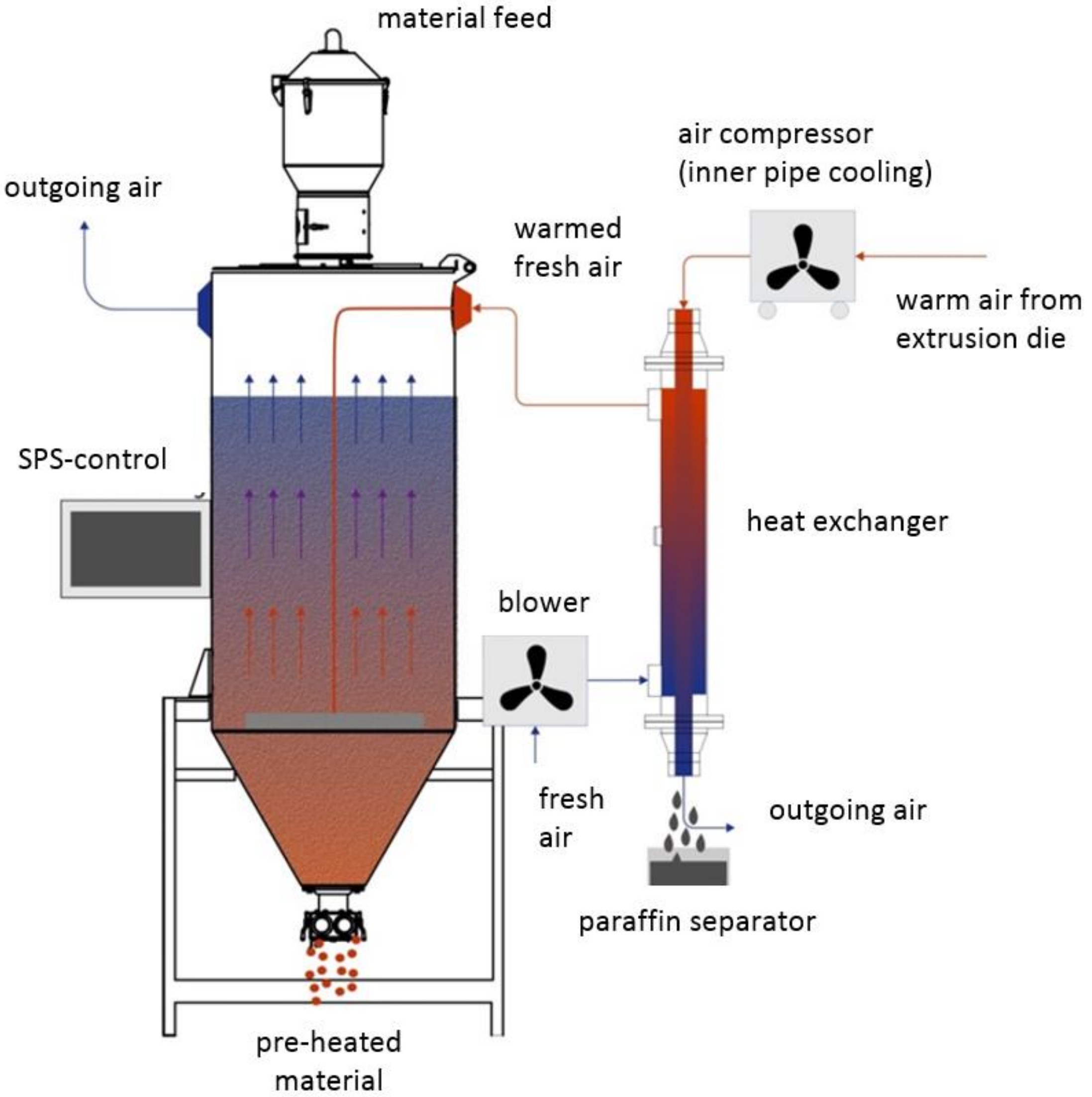

Figure 4.6: Concept of preheating from inner pipe cooling

The hot air coming from the extrusion die streams through a heat exchanger, to warm up clean ambient air. The condensing paraffin drips out of the vertical arranged heat exchanger to avoid clogging of the flow channels. The ambient air is blown by a compressor and streams through the pre-heater after the heat exchanger. Inside the pre-heater, the warm air transfers the heat to the cold granules, which are continuously filled to the top of the pre-heater. The complete test set-up is shown figure 4.7.

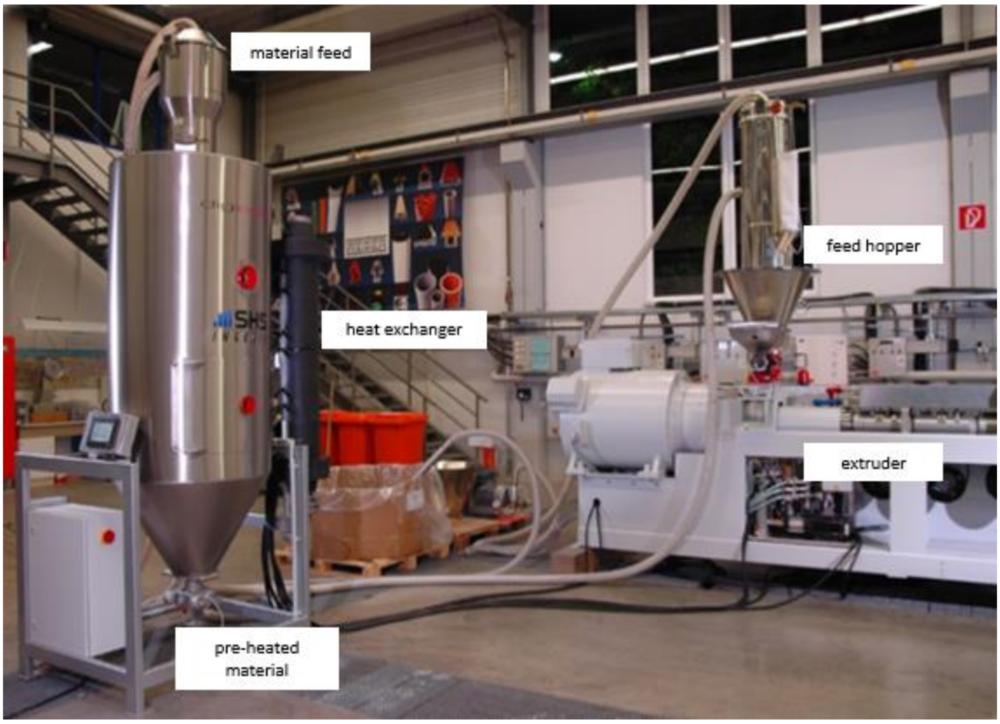

Figure 4.7: test set-up for material pre-heating

4.4 TEST CONDITIONS

The tests are performed using an extruder of Hans Weber Maschinenfabrik (Kronach, Germany). The measurements take place during production of a pipe with dimensions of 250mm outer diameter and 22,7mm wall thickness. Material is PE100, which is an often used pipe material. The output of the extruder is 700kg/h.

The last three zones of the extruder cylinder are equipped with a central suction blower for cooling. Pneumatic valves as well as manual valves for fine-tuning are installed below the zones to control the air-flow and thus the temperature of the zones.

Furthermore the extrusion die allows inner pipe cooling. During the production it is possible to switch between the two heat-sources “extruder barrel” and “inner pipe cooling” to feed the pre-heater. In case of using the extruder barrel as heat source, the warm air is not polluted and so the usage of the heat exchanger is not necessary. Using the heat-source of the inner pipe cooling, there is one test within and one test without using the heat exchanger.

4.5 RESULTS: EXTRUDER BARREL COOLING.

The last three zones of the extruder are cooled using a centrally arranged suction blower. At a stable process, there is an airstream of 251 kg/h to realize the cooling of the three zones to the temperatures defined before. The ambient temperature of 24°C rose to a temperature of 70°C. That means that there was usable waste-heat of 3,3kW inside the airstream.

In the considered process, the amount of waste heat in the last three zones of the extruder cylinder was 3,3kW. But the amount of waste heat in extrusion processes depends on a lot of factors, e.g. turning speed of screw, screw design, material, output rate, counter pressure, mixing parts etc. There are many processes in which waste heat of 5-10kW is available from the extruder barrel, especially when there is a high turning speed of the screw [4].

The considered process is not ideal for usage of the waste heat from the barrel due to low cooling energy. But there are many other processes, where the technology from the test set-up can be adapted and lead to economical interesting results.

4.6 RESULTS: INNER PIPE COOLING.

The process conditions for the test are the same as described above when using the extruder barrel as waste heat source.
At first, there is a test using the heat exchanger. The warm air from the inner pipe cooling streams through the heat exchanger to warm up ambient air. But there is an influence to the global production process. The blower, that is sucking the air through the pipe, can no longer lead the warm air into the free environment, but has to put it through the heat exchanger. The heat exchanger has small flow channels, which leads to a counter pressure, which is too big for the blower. The air flow is reduced in the moment the heat exchanger was integrated into the set-up. That is a problem in the process, because a reduced air-flow means also a reduced cooling power for the inner pipe surface. A bigger heat exchanger with bigger flow channels could be a solution to that problem, but with increasing size the price raises more and more and the pre-heating is no more economical. For that reason, the second test without using a heat exchanger is done. The pressure drop is much lower without a heat exchanger and the cooling power for the inner pipe surface is still enough.

The air is leaving the extrusion die at a temperature of 116°C and is directly lead into the pre-heater. Leaving the pre-heater at the top, all of the thermal energy was transferred to the granules inside the pre-heater and the air temperature is 19°C. This is the same temperature as that of the continuously filled granules.
The temperature of the warmed granules rose from 19°C to 31°C with an output of 700kg/h. Which means that 5kW of heat was transferred to the granules.
Having a look at the power consumption of the extruder line in total, it is reduced from 190kW to 185kW, as shown in figure 4.8.

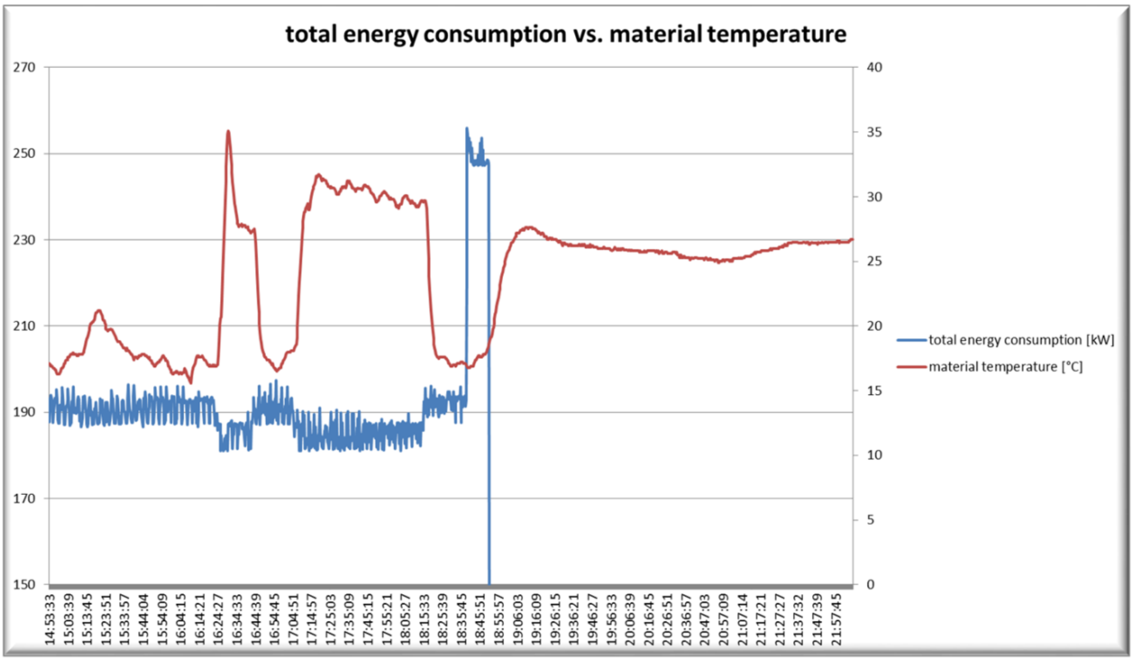

Figure 4.8: result-graph - savings from inner pípe cooling

The graph shows in the red line a temperature profile, which changes during time due to different pre-heating temperatures. It is clearly visible, that a higher pre-heating temperature leads to a lower energy consumption of the extrusion line. The energy consumption decreases from 190kW (material: 19°C) to 185kW (material: 31°C).

The blower used for the inner pipe cooling was too small, to suck enough air through the extruded pipe to warm the material up over 31°C. With a stronger blower, there would be more cooling power and thus more energy to warm up the material. A realistic value is 60°C.

What is visible from the test is that a temperature raised about 12K leads to a reduction of the energy consumption of 5kW. Assuming linear behavior, a temperature raised about 41K (60°C pre-heating temperature) can lead to savings of 17kW. In this test a reduction of 2.6% of the energy consumption is visible by pre-heating the material from 19°C to 31°C. Pre-heating the material from 19°C up to 60°C would lead to potential savings of 9% of the total energy consumption.

To prove the findings from the first test, a second test is carried out with another process. In this second test, a pipe of PE100 material is extruded with a rate of 510kg/h. This time, a bigger blower allows a pre-heating of the material from 18°C up to 63°C. This time the energy consumption of the extruder drive is measured. The energy consumption of the drive decreases from 85kW at 18°C to 79kW at 63°C. That is a saving of 7%. Further savings of 1-2% are expected to arise from the cylinder heaters, which are also relieved due to the pre-heating. So the assumption from the first test is proved, that a pre-heating of the material leads to savings up to 10% of the energy consumption.

4.7 CONCLUSIONS

In the context of this project, two ways to use waste heat in pipe extrusion for material pre-heating were reviewed:

1. Waste heat from extruder barrel cooling
2. Waste heat from inner pipe cooling

Both cases can be (economically) interesting, if the processes are chosen well. The considered process allows heat recovery of 3,3kW from the cooling of the last three cylinder zones. Compared to the total energy consumption of 190kW of the extrusion line, this recovery seems small. But research showed that there are other processes in the market, where the applied technology can earn more savings in smaller processes and thus work economically.
Using the waste heat from the inner pipe cooling, it was proved in two test series, that energy savings up to 10% of the consumption can be earned when pre-heating the material to a level of 60°C - 65°C. The usage of a heat exchanger could not be realized economically, so this set-up is only possible with material having a moderate emission of paraffin.

4.8 RECOMMENDATIONS FOR FURTHER RESEARCH

The results of the project are very interesting, especially for the pre-heating using waste heat from the inner pipe cooling. But there are still some challenges left, to bring the technology to industrial application.

- Filtering of paraffin is a problem. At the moment, it is only possible to pre-heat material directly with heat from the inner pipe cooling, which can be polluted. Long term test series can show if there is a problem when using the polluted air to pre-heat the material.
- Using air from the extruder barrel to pre-heat the material, lower savings can be expected. Further developments should focus to find a technical solution with lowest possible invest. At the moment, pay-back time takes several years, because the control valves under the cylinder are much more expensive than the decentral blowers that are used today.

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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.

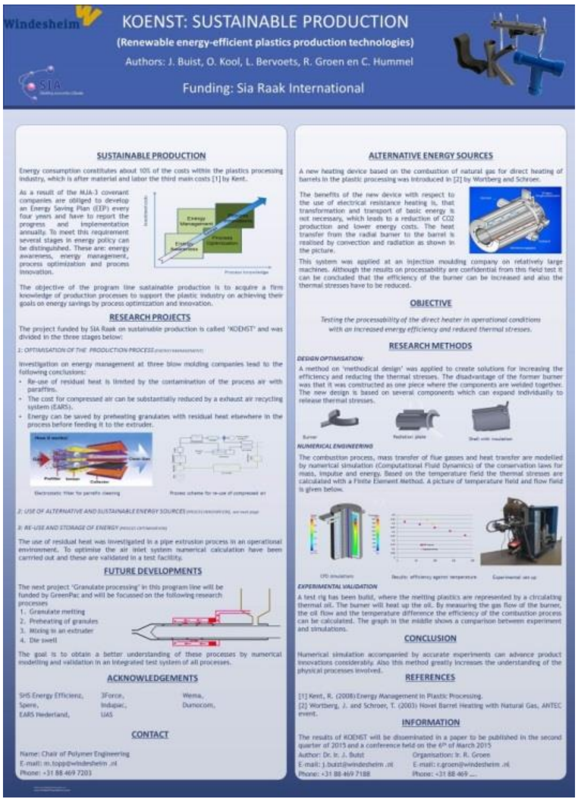

Figure 4.1: Poster presentation

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.

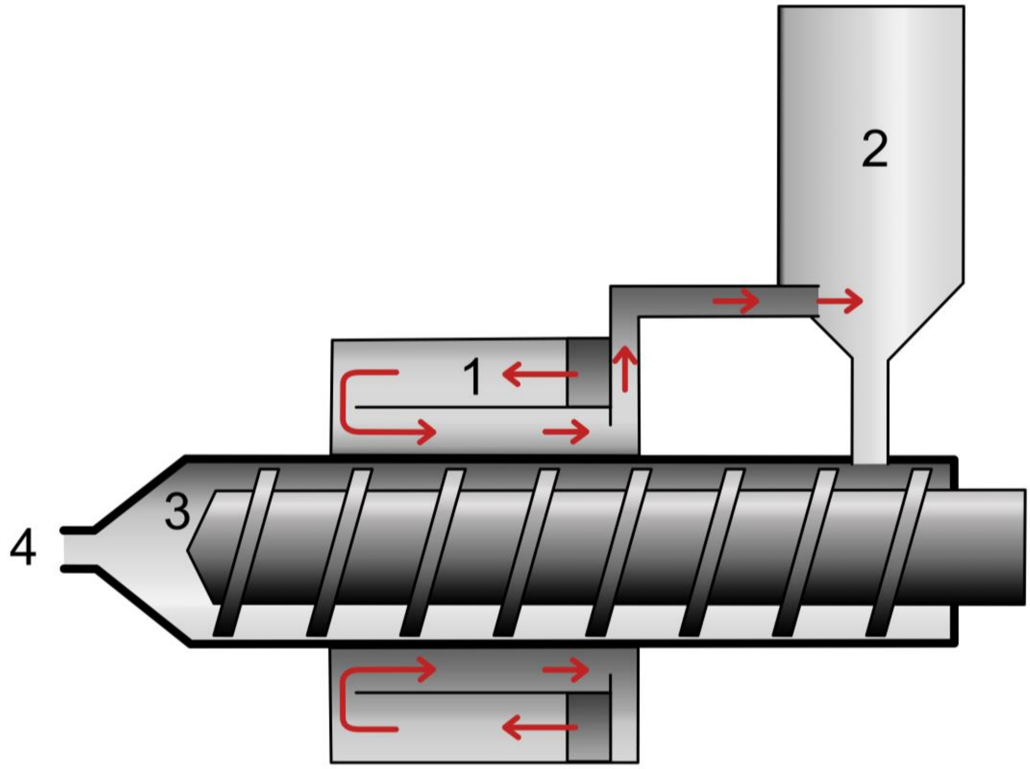

Figure 4.3: Scheme for future developments

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?

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