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USING SECONDARY AIR COOLING IN BLOWN FILM EXTRUSION: CONCEPT DESIGN AND EXPERIMENTAL STUDY

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Abstract

The characteristics and the quality of a blown film are strongly influenced by the stretching and simultaneous cooling of the molten polymer within the bubble formation zone. Moreover, the output rate of the process is generally limited by the cooling rates and the stability of the bubble. As a consequence, the design of cooling systems is highly relevant in terms of process optimization. Beside intensifying the heat removal, the concept of secondary air cooling aims at eliminating unsteady ambient influences during bubble formation and increasing bubble stability. Different concepts for cooling systems with integrated secondary air cooling are presented and experimentally tested. The results confirm that the implementation of secondary air cooling is feasible and generally supports bubble cooling regarding the aforementioned intention. Furthermore, the study reveals that an accurate design of such cooling systems is required.

Introduction

In polymer processing, blown film extrusion is an important production process for thin films. The extrudate exits from an annular die gap and forms a tubular film bubble as it is inflated by air. At the top of the plant the bubble passes a collapsing device and two nip rolls which draw down the film. To transform the polymer melt into a solid film, extrudate cooling is necessary. In conventional blown film extrusion an air ring blows cooling air at the outer surface of the bubble around its circumference. Additional internal bubble cooling is often used to intensify the cooling which is generally the limiting factor regarding the maximum output rate in production processes. A state-of-the-art blown film line is fully automated and achieves an output rate exceeding 1000 kg/h. The layflat width is regulated by the amount of inflating air, the target film gauge is controlled by the haul-off speed and film thickness profile control tends to provide a uniform film gauge around the bubble circumference.

Besides high cooling rates, an effective cooling system should meet at least two more requirements. Firstly, it has to stabilize the bubble and secondly, it has to prevent it from unsteady ambient conditions in the production environment. Theoretically, increasing the (volume) flow rate of the cooling air leads to faster solidification of the melt which, in turn, allows higher output rates. Practically, this might affect bubble stability and causes variations in quality or even product defects [1]. The exposure of the sensitive film bubble to hardly controllable influences, such as draft, contamination or temperature fluctuation, enhances these negative effects [2].

Against this background, the concept of secondary air cooling is developed. The basic idea is to provide conditioned air by means of a second independent inlet within the bubble formation zone, which is the segment of the bubble between the die exit and the frost line. In contrast to primary cooling air, secondary air is not directly blown towards the film bubble at a high velocity, but rather used to create a steady and controllable environment by replacing unsteady ambient air [3]. This requires additional isolation of the bubble formation zone. Consequently, primary and secondary air cooling as well as a bubble enclosure have to be integrated into one combined cooling system. In this context, conditioned air means that the amount of secondary air, its (volume) flow rate, the temperature and the flow direction are defined or adjusted by the operator in accordance with the design of the system. In sum, the concept aims at eliminating unsteady ambient influences, improving bubble stability and intensifying bubble cooling.

Different concepts for bubble cooling systems and bubble enclosures are extensively discussed by various authors. An overview on cooling systems is given in [4]. The principle of countercurrent cooling in combination with a shroud is investigated in [5]. Using an additional air streams to separate the bubble from ambient air is presented in [6]. A flexible shroud as guiding-element for the cooling air is presented in [7]. Most recently, the development of a cooling system with an air-ducting membrane made of silicone is investigated in [8].

Concept Design

Three concepts for cooling systems with integrated secondary air cooling were developed at the Institute of Product Engineering at the University of Duisburg-Essen. All three concepts are based on a conventional single-lip air ring which is declared as the primary air ring. An additional air-guiding element is installed having two major effects. Firstly, it keeps the air stream close to the film bubble. Because of the smaller gap between the guiding-element and the bubble the air accelerates in this area leading to a lower pressure. This phenomenon is known as the Venturi effect [9]. Consequently, the film bubble moves towards the guiding-element and hence is stabilized. Secondly, air from the back side of the guiding-element is aspirated due to the low pressure and reinforces the primary cooling air stream. Moreover, the three systems include bubble enclosures which insulate the bubble from the production environment and therefore avoid contamination of the film or any unsteady influences. However, the structure of the enclosures and the design of the outflow at the top as well as the way the secondary air is provided within the systems are fundamentally different among the concepts.

Concept 1: Co-current Secondary Air

Concept 1 is taken from [3] where it has been presented for the first time. Figure 1 shows the CAD model of the concept which is characterized by co-current flow of the secondary air. This means that the secondary air, similar to the primary cooling air, is provided at the bottom of system and follows the upward flow direction of the air stream. Here, the intention is to take advantage of the Venturi effect, which occurs due to the air-guiding element, so that the main air stream is reinforced by aspirated secondary air. A conventional air ring with a radial outlet serves as a reservoir providing secondary air with defined temperature and volume flow rate at rather low velocity. At this point, the concept differs from a dual-lip air ring, which blows two separate air streams at high velocity directly towards the bubble. The enclosure consists of a rigid shroud and an iris used as top cover. This allows to vary the size of the outlet for the outflowing air and should prevent ambient air from entering the system.

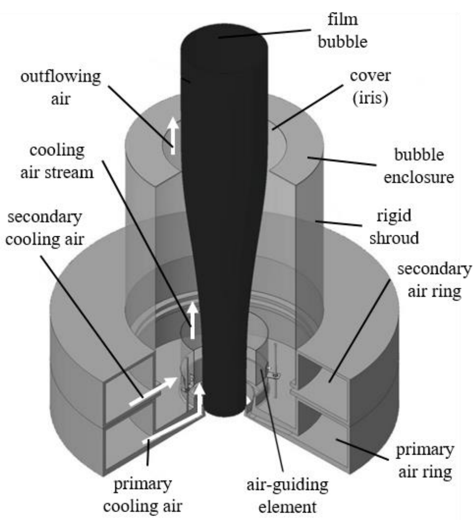

Figure 1. Illustrative CAD model of concept 1 for secondary air cooling.

Concept 2: Countercurrent Secondary Air

Turning the flow direction of the secondary air leads to concept 2. As shown in in Figure 2, a secondary air ring, located at the top of the enclosure, provides the secondary air and blows it downward along the inner surface of the rigid shroud. A simple cylindrical enclosure would force ambient air to enter at the top because of the fast and entraining primary air stream and low pressure. Against this background, the system is fed with secondary air instead to eliminate unsteady ambient influences. Moreover, the secondary air should intensify the bubble cooling.

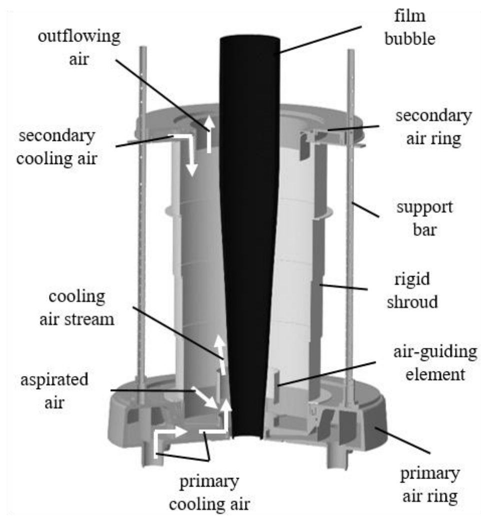

Figure 2. Illustrative CAD model of concept 2 for secondary air cooling.

The rigid shroud in concept 2 is designed as a telescope unit consisting of four elements and the secondary air ring is fixed by support bars. Thus, it is possible to adjust the height of the enclosure according to a particular operating point. On top of that, the operation of the system, for instance during the start-up of the machine, remains comfortable due to the telescope function.

Concept 3: Perforated Basket

The basic idea of concept 3 is to provide secondary air along the entire bubble formation zone. Again, a large amount of secondary air at low velocity and a defined temperature is desired. To manage that, a double-walled enclosure with a rigid shroud on the outside and a perforated shroud on the inside is used. Figure 3 shows the CAD model of concept 3. The volume in between the two walls serves as a distributing reservoir for the secondary air. In this case, an additional air ring is installed at the bottom of the enclosure and is used to feed the reservoir. The perforated shroud as well as the cross section of the enclosure require an accurate design so that the secondary air is distributed homogeneously within the entire system.

As a prototype for this concept does not exist yet, it is not included in the presented experimental study.

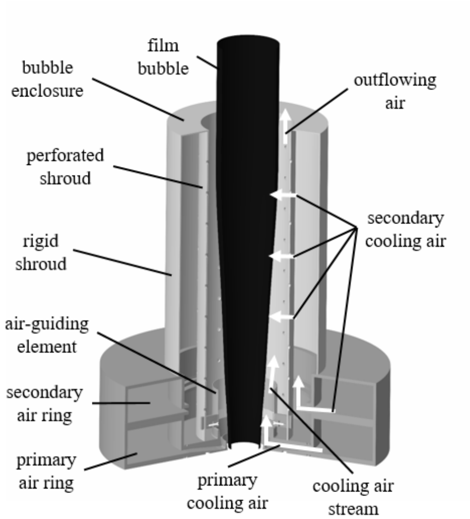

Figure 3. Illustrative CAD model of concept 3 for secondary air cooling.

Experimental Study

A series of experimental runs is carried out for concept 1 (run a-k) and concept 2 (run 1-9). Details on the runs and a description of the procedure are given in a separate section (compare Table 1 and Table 2). The experimental study of concept 1 (run a-k) has been originally presented in [3]. Due to a time offset and changes in the machine configuration some deviations appear within the experimental set-up for both concepts. Nevertheless, no considerable influences on the qualitative results are expected because the basic material is equal and the underlying processing conditions are as similar as possible.

Materials

The polymer used in this study is a low-density polyethylene (LDPE 2100N0), manufactured by SABIC. It has solid density of 921 kg/m³ and a melt flow rate of 0.33 g/10min at 190 °C and 2.16 kg. To improve the optical detection of the bubble contour and the frost line height (FLH), colored batches are added. For run a-k a black batch and for run 1-9 a blue batch is added with a concentration of 1.5 % and 5 %, respectively. Both batches are manufactured by A. Schulman.

Equipment

A small-scale blown film line with a die diameter of 100 mm and a die gap width of 1 mm is used. Run a-b (concept 1) are performed with a single-layer die and a grooved-barrel extruder (Ø 48 mm/24 D) [3]. In contrast, the machine is equipped with a three-layer coextrusion die and two additional grooved-barrel extruders (Ø 35 mm/25 D and Ø 30 mm/25 D) for run 1-9 (concept 2). All three extruders are fed with the same material mix and thus no explicit multi-layer film is produced. Ambient air, provided by a fan and distributed by a conventional single-lip air ring, serves as primary cooling air. An additional fan coupled with a chiller supplies the systems with prechilled secondary cooling air. The machine regulates the output rate as well as the thickness and the layflat width of the film.

Procedure

Prototypes for both concepts are assembled according to the presented CAD models and mounted on the primary air ring. The enclosures and the air-guiding elements are made of a transparent, robust PET-film so that the film bubble is visible. A steady process with an output rate of 35 kg/h and a film thickness of 100 µm is the basis for all experimental runs. For both concepts, the settings for the heater band temperatures of the extruders and the dies are equal. The temperature at the die exit is set to 195 °C. In contrast, the blow-up ratio (BUR) and the layflat width differ. It is BUR=2 and BUR=3 for run a-k (concept 1) and run 1-9 (concept 2), respectively.

Table 1. Cooling conditions and resulting frost line heights for the experimental runs with concept 1 (BUR=2) [3].

Run	$\dot{V}_P$ [m³/h]	T_P [°C]	$\dot{V}_S$ [m³/h]	T_S [°C]	Ø-Iris [mm]	FLH [m]
a	399	23	-	-	-	0.888
b	710	23	-	-	-	0.440
c	399	23	328	25	-	0.865
d	399	23	329	20	-	0.806
e	399	23	331	10	-	0.738
f	399	23	326	10	395	0.748
g	399	23	332	10	285	0.905
h	399	23	326	10	215	0.913
i	399	23	382	10	395	0.855
j	399	23	459	10	395	0.841
k	399	23	656	10	395	0.740

In order to test the effect of secondary air cooling, the volume flow rate and the temperature of the secondary cooling air is varied. Table 1 and Table 2 provide detailed information about the cooling conditions for concept 1 and concept 2, respectively. Primary cooling air conditions remain constant, except for run b and run 9 which serve as a reference. Run a and run 1, where secondary air cooling is switched off, are used as a reference, too. The volume flow rates and air temperatures are measured with an anemometer and a temperature sensor. To detect the frost line height, a digital camera takes high-resolution images of the film bubble and a validated computational routine extracts the outer contour of the bubble [10, 11]. The position, where the bubble diameter starts to be constant, is determined as the frost line height. Finally, the effect of different cooling conditions can be evaluated by means of the resulting positions.

Table 2. Cooling conditions and resulting frost line heights for the experimental runs with concept 2 (BUR=3).

Run	$\dot{V}_p$ [m³/h]	T_p [°C]	$\dot{V}_s$ [m³/h]	T_s [°C]	FLH [m]
1	606	27.3	-	-	0.565
2	607	29.4	483	19.9	0.584
3	605	29.4	598	20.6	0.595
4	604	29.5	722	20.5	0.593
5	591	32.0	483	10.6	0.598
6	590	31.4	598	10.5	0.612
7	604	30.7	722	8.0	0.588
8	602	30.5	850	8.6	0.584
9	419	30.0	850	8.6	0.841

Besides the cooling conditions, the diameter of the iris at the top of the enclosure (concept 1) is varied. A diameter of 395 mm in Table 1 corresponds to a fully opened iris. In run c-e no iris is mounted so that the outflow equals the diameter of the shroud, namely 450 mm. As a reference, run a-b are performed without any enclosure, which also applies to run 1 (concept 2) in Table 2.

Results and Discussion

Figure 4 illustrates the effects of varying cooling conditions on the frost line height for concept 1. First of all, run 1 and run 2 demonstrate that the primary air stream has a major influence on the bubble cooling, which meets the expectations. An increase of the primary volume flow rate of approx. 80 % leads to a reduction of the frost line height of 50 %. Run c-e show the influence of the secondary air temperature. It is obvious that the frost line height decreases with lower temperatures. A temperature reduction of 15 °C lowers the frost line height by approx. 15 %. As described earlier, the diameter of the iris at the top of the enclosure can be adjusted. The results of run f-h confirm that the design of the outflow of the bubble enclosure is highly relevant. A narrow outflow (run g-h) seems to have a bad influence on the bubble cooling as the frost line height is significantly higher, namely approx. 20 %, in comparison to a fully opened iris (run f). This might be caused by an accumulation of heated cooling air below the cover and within the enclosure [3]. In contrast to the primary air, run i-k reveal that the volume flow rate of the secondary air has no remarkable influence on the frost line height. Taking the position of the secondary air inlet into account, it can be concluded that the additional secondary air does not necessarily strengthen the aspirated air stream below the air-guiding element, which is one of the basic ideas of this concept. Comparing run i-k with the reference (run a-b) makes clear that additional secondary air generally contributes to the bubble cooling as the frost line height reduces. However, an equal increase of the primary volume flow rate is much more effective, yet this might be limited in terms of bubble stability.

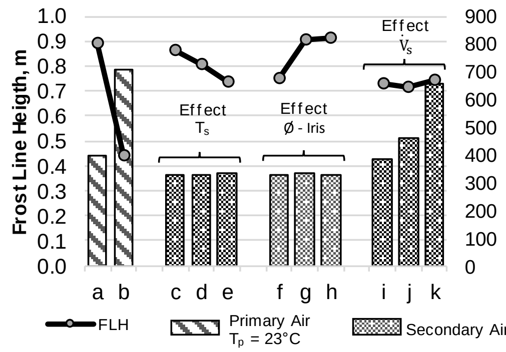

Figure 4. Effects of varying cooling conditions on the frost line height for concept 1 (BUR=2), corresponding to Table 1 [3].

The experimental results for concept 2 are shown in Figure 5. It is striking that neither the volume flow rate of the secondary air nor its temperature has a significant effect on the frost line height. In comparison with the reference, which is performed without the shroud (run 1), the frost line height even tends to rise for run 2-7. Consequently, the secondary air in this case does not contribute to the bubble cooling at all. Instead, an accumulation of heated primary cooling air within the enclosure might occur once again. Moreover, the secondary air probably does not mix with the primary air stream below the frost line. This would explain the lack of any remarkable indication for temperature effects comparing run 2-4 and run 5-7.

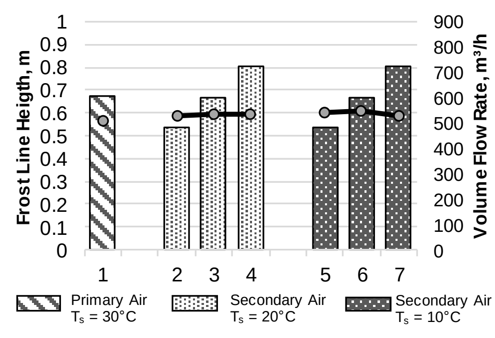

Figure 5. Effects of varying cooling conditions on the frost line height for concept 2 (BUR=3), corresponding to Table 2.

For run 8-9 the maximum possible volume flow rate of secondary air is provided. As Figure 6 illustrates the secondary air still does not intensify the bubble cooling. In contrast, the reduction of the primary volume flow rate by approx. 30 % leads to an increase of the frost line height by more than 40 %. This indicates that the position of the secondary air inlet in concept 2 has to be adjusted according to the underlying operating point, especially with respect to the frost line height.

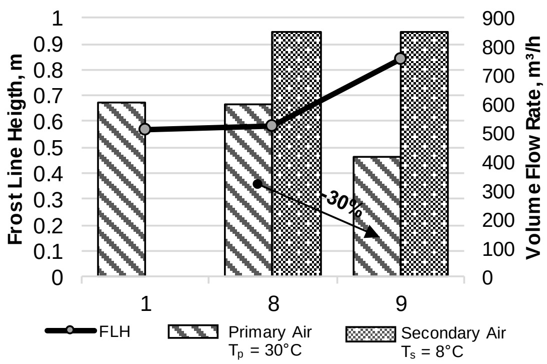

Figure 6. Comparison of the effect of primary and secondary air cooling on the frost line height for concept 2 (BUR=3), corresponding to Table 2.

Besides the influence of the secondary air on the bubble cooling, the bubble stability and the flow direction of the air at the outlet of the enclosure are observed during the experiments with concept 2 (run 2-9). Generally, a stable bubble is obtained for all experimental runs. With respect to the idea to avoid any contamination or unsteady environmental influences within the bubble formation zone, concept 2 is suitable because no ambient air enters the system. This is indicated by little flags which are attached to the secondary air ring at the outflow.

To sum it up, the experimental results for concept 2 indicate that the configuration of the system is not yet sufficiently adjusted to the underlying process. However, it is assumed that the intended contribution to the bubble cooling can be obtained. Further investigations are planned in order to improve the system. Due to the telescope function of the enclosure it is possible to manipulate the height of the secondary air inlet. This is required to enhance the distribution of the secondary air within the enclosure. In this context, numerical flow simulations help to analyze and to evaluate the effects of varying boundary conditions on the bubble cooling and, for this reason, serve as a basis for the continuing development process of the concept.

Conclusions

The concept and intention of secondary air cooling is explained and three different concepts for practical implementation are presented. Prototypes for concept 1 and concept 2, using co-current and countercurrent secondary air, are assembled and experimentally tested. The results for concept 1 confirm that secondary air generally contributes to the bubble cooling. In contrast, the tested configuration of concept 2 hardly influences the heat removal from the film. This is explained by an insufficient adjustment of the cooling system to the underlying process. Consequently, further development and improvement are required to demonstrate the potential of this concept. Apart from that, the experimental runs verify that ambient influences on the bubble formation process are prevented successfully with the help of enclosures. Because of the higher complexity of concept 3, its prototype design requires even higher accuracy with respect to the operating point. For this reason, an experimental study with concept 3 is not yet intended. Instead, further investigations still focus on concept 2, which is considered to be more promising.

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