Effect of film fabricating conditions and its implications on mechanical properties of high-density polyethylene film

B Herlambang and M R O B Anando
Research and Development Department, PT Chandra Asri Petrochemical, Tbk., Cilegon, Banten 42447, Indonesia

Corresponding author’s email: grouprnd@capcx.com

Abstract. The use of plastics, especially High-Density Polyethylene (HDPE) film has increased rapidly in recent years due to its low cost, lightweight and excellent mechanical properties which is depended on the extrusion condition in the owner’s film fabrication machine. The blown film process is the common process used to make a thermoplastic film in large volumes. However, many research performed long ago in the mechanical properties of polyethylene only concerned on the effect of conventional processing parameters such as temperature and pressure in blown film machines and neglected the significant effect of critical extrusion conditions. We did the study to know the effect of critical extrusion conditions such as output rate, blow-up ratio (BUR) and neck-point height (NPH) which was intended to get the optimum film fabrication conditions in a blown film extrusion machine. Each parameter was performed in five different conditions by increasing one parameter and controlling the other. The resin first melted, conveyed, and delivered before finally blown to form the film. The mechanical properties observed were impact resistance, tensile strength, elongation, tear strength, and young modulus. The result indicates that increasing the output rate, BUR and NPH imparted in the film’s orientation balance, bubble shape, relaxation, and crystallization effects will lead to the increase of impact resistance, decrease of tear strength, and balance of film direction properties. The excessive and low amount of output rate, BUR and NPH are not desirable as it decreases the mechanical properties from HDPE film whether in mechanical direction or transverse direction. Hence, the optimum operating condition depends on which mechanical properties that needed to be achieved by film fabricators.

Keywords: HDPE film, blown film extrusion, operating condition, mechanical properties

1. Introduction
High-Density Polyethylene (HDPE) is made by low-pressure methods that polymerized in the presence of Ziegler-Natta (ZN) catalyst. The HDPE resins are used for the manufacture of heavy-duty films for fertilizers, planting, and bags/containers [1]. Other applications include pipe, monofilament, and injection. Processing HDPE is somewhat different than processing Low-Density Polyethylene and Linear Low-Density Polyethylene, because of its higher degree of crystallinity, more consistent structure, high strength, and stiffness among polyethylene grades. In addition, HDPE has reasonably good barrier properties owing to its high degree of crystallinity, because its crystalline regions block the travel of gas molecules much better than amorphous regions [2]. The HDPE is preferably to be converted by the film blowing process, instead of cast film due to better property balance, less scrap, and low
equipment cost [3]. Converted HDPE films are commonly used in numerous packaging where its mechanical response is excellent, moreover, in today’s demanding packaging applications, high strength of films are essentials. It is, therefore, necessary to determine the optimum processing conditions in order to reap the full benefits of HDPE by using blown film machine. However, a lot of research in the mechanical properties of polyethylene concerned on the effect of conventional processing parameters such as temperature and pressure on these properties [4]. Although long ago, Piggot showed that extrusion conditions could have a profound effect on the mechanical properties of polyolefin, studies have neglected the significant effect of critical extrusion conditions [5]. Several authors have attempted to correlate the mechanical properties of blown film with the kinematics and dynamics of the process. Campbell claimed that the plastic strain, as the strain put in the film after the onset of crystallization, correlated with mechanical properties, such correlation based on a limited set of experimental data are easily questionable as the quantitative determination of the plastic strain and strain stress is a very difficult task [6]. Simpson and Horison have investigated the film blowing processing conditions effects on crystalline and amorphous morphologies of HDPE and their relation with film properties. Some changes can lead to the change film’s lamellae stacking and orientation both in Machine Direction/MD (where the film direction moves through the machine from the start to finish) and Transverse Direction/TD (where the direction perpendicular to the MD) [7]. The previous study shows that the change of critical extrusion parameters and its effects on film mechanical properties haven’t much yet explored. Thus, the purpose of this study is to know the effects of some critical extrusion parameters (output rate, blow-up ratio, and neck-point height) to the properties of HDPE film.

2. Materials and method

2.1. Materials
All of the polymer materials used were HDPE synthesized by ZN Catalyst with the following fundamental properties as shown in table 1.

2.2. Blown film extrusion process
Blown film extrusion is one of the most common used for polymer processing methods. This technique usually produced by using a single screw extruder and temperature of the die is 200 °C and a thickness of 20 μm for each layer. The resin was first melted by subjecting it to heat and pressure inside the barrel of an extruder then conveyed and delivered in a vacuum system before finally forcing the melt through a narrow slit in a die to control its diameter and thickness [8]. The Yoshii Blown Film Machine (BFM) was used and the both materials in the same machine condition were set to prevent the effect of process condition to the final product.

2.2.1. Output rate. In blown film extrusion, screw speed controls the output more than any other factor. Generally, the higher the screw speed, the higher is the output. The output rate of a Yoshii BFM (Q) was calculated by following equation:

\[ Q = \pi D V_f T_f \rho \]  

where \( \rho \) is film density, \( V_f \) is the die exit and final film velocities, \( T_f \) is the initial and final film thickness.

| Table 1. Fundamental properties of HDPE. |
|------------------------------------------|
| Fundamental properties | Test method | Unit | HDPE-1 | HDPE-2 |
|------------------------|-------------|------|--------|--------|
| Melt Index (190 °C and 21.6 kg load) | ASTM D 1238 | g/10 min | 15 | 10.5 |
| Density | ASTM D 1505 | g/cm³ | 0.950 | 0.953 |
2.2.2. **Blow-up ratio (BUR).** The blow-up ratio (BUR) is described as the ratio of bubble diameter ($D_b$) per die diameter ($D_D$). It defines how the bubble has expanded seen in the transverse direction. The BUR is calculated by:

$$\text{BUR} = \frac{D_b}{D_D} = \frac{2 \times \text{ Lay flat width}}{\pi \times D_D} \quad (2)$$

The lay-flat film width (LFW) is the collapsed bubble width before slitting given by $\text{LFW} = 1.57 \times D_D$.

2.2.3. **Neck-point height (NPH).** Neck-point height is normally expressed by the distance from the die surface to the point where the necked diameter of the bubble becomes the shortest. The NPH is usually used by a highly skilled person after visually determines the location of the frost line.

2.2.4. **Processing variables.** To conduct the experiment, several adjustments need to be determined and listed in table 2.

2.3. **Testing methods**

The testing process of the film will separately differ into two steps for some test items, a machine and transverse direction. The machine direction is where the film set in parallel against the direction of polymer orientation while the transverse direction is where the film set in perpendicular against the machine direction. All the tests were conducted in a room with a temperature of 23 °C and 50 % RH.

2.3.1. **Film impact.** This method determines the resistance of film to impact-puncture penetration. The energy required for fracture, to burst, and penetrate a with the material or a measurement of the resistance against mechanical shock by pendulum according to ASTM D3420. If film impact strength value is high, the strength is better (stronger).

2.3.2. **Dart impact.** This method determines the required energy leads to the plastics failing under certain situation of a free-falling dart. The amount energy is expressed by the mass of the falling weight from a specified height which would result in a 50 % failure of specimens tested according to ASTM D1709.

2.3.3. **Tensile strength.** This method is the load-carrying capability of the film and measured by pulling the end of a rectangular strip at a specified rate in the opposite directions until it breaks and reported as the force at a given point divided by the original cross-sectional area (width multiplied by thickness) of the specimens which mostly reported at the yield point (where the force in the film begins to drop after an initial rise) and the breakpoint. The specimens were tested on a Universal Testing Machine according to ASTM D882.

2.3.4. **Elongation.** Another property covered by the same ASTM method as that for tensile strength is elongation, described as the ability of the film to stretch prior to breaking or yielding. A material that stretches significantly prior to the breakpoint is called a ductile, while the one that breaks after only

| Table 2. Processing variables of blown film extrusion machine. |
|-----------------------------|-------------------------------|-----------------|
| **Parameter**               | **Controlled variable**       | **Manipulated variable** |
| Output rate                 | BUR 3.8:1; NPH 35 cm          | 20; 25; 29; 33; 35 kg/h |
| BUR                         | Output 29 kg/h; NPH 35 cm     | 3; 3.5; 3.8; 4; 4.5 |
| NPH                         | Output 29 kg/h; BUR 3.8:1     | 20; 25; 30; 35; 40 cm |
a small degree of stretching is called brittle. Elongation is reported as a percentage and calculated by dividing the extension achieved in the specimens at the break by the original length and multiplying by 100 according to ASTM D882.

2.3.5. Tear strength. This method defines the force needed to propagate tearing in a film or non-rigid sheet using pendulum swing with initial rips of an Elmendorf-tearing tester according to ASTM D1922.

2.3.6. Young modulus. Another property covered by the same ASTM method as that for tensile strength and elongation is tensile modulus. Young modulus is an index of the stiffness of thin plastic sheeting. The reproducibility of test results is good when the precise control is maintained over test conditions according to ASTM D882.

3. Results and discussion

3.1. Effect of output rate
Increasing the output rate will be affected by increasing the screw speed and maintain the take-up ratio in BFM [2]. In this experiment, we implemented 5 output variations i.e. 20; 25; 29; 33 and 35 kg/h. The fast take-up and screw speed, lead to a short residence time of the molten polymers and gives an effect to higher strength in the film [9]. These variations exhibit a higher film impact and dart impact as the output increased which can be seen in figure 1. Fast take-up speed causes a large neck down in the bubble and gives an effect in short residence time, any processing condition that causes faster cooling will improve the impact strength. Fast cooling yields small spherulites and low crystallinity [10]. It can be seen that HDPE-1 yielded a higher value of film impact and dart impact as the lower density lead to a higher value in impact properties [11].

In figure 2a, it can be seen that as the take-up and screw speed run faster to obtain a higher output rate, lead to a melt drawing that occurs simultaneously in both machine and transverse direction with the former predominating [9]. This will balance the orientation results and increase the tensile strength at yield and at break in both MD and TD properties. But at the freeze line where the residual orientation and stresses are retained as the non-crystalline region, instead of the crystalline, so the elongation in both directions will gradually decrease as the output rate increases during the fabrication process as can be seen in figure 2b [10]. It also can be seen that HDPE-2 yielded a higher value in tensile strength both at yield and at break as the increase of density will result in a higher value, contrary to the elongation which will be lower because the elongation at break tends to respond in the opposite manner to the tensile strength [11].

![Figure 1](image)

Figure 1. Effect of output rate on impact resistance.
In figure 3, the value of tear strength and young modulus decrease as the output rate increases because the modulus is expected to be governed by the non-crystalline portion [12]. The comparison between HDPE-1 and HDPE-2 exhibits a higher value in HDPE-1, but it is in contrary to the fact that the increase in MI and decrease in density will give a lower value in young modulus property [11].

3.2. Effect of BUR
Increasing the blow-up ratio will be affected by adjusting the bubble diameter and maintaining the bubble stability in BFM. In this experiment, 5 BUR variations i.e. 3; 3.5; 3.8; 4 and 4.5 were implemented. This adjustment leads into the output film width (BUR 3:1 gave 350 mm film width; 410 mm; 450; 470 and 530 mm, respectively [2]. These variations exhibit a higher film impact as the BUR increases from 3:1 to 4.5:1. As seen in figure 4, when the blow-up ratio becomes larger, the transverse direction molecular orientation also becomes higher with the corresponding decrease in the drawdown ratio. This will cause a reduction in cooling time [3]. Any processing condition that causes faster cooling will lead to improve the impact properties (film and dart impact) [10]. The comparison between HDPE-1 and HDPE-2 exhibits a higher value in HDPE-1 as the density increases leading to a lower value in film impact property [11].

In figure 5, tear properties and the young modulus are significantly changing following the change of molecular orientation, when the BUR increase, an insignificant change or constant in MD and lower tear strength in TD [3]. The comparison in tear strength between HDPE-1 and HDPE-2 exhibits a higher value in HDPE-1 as the increase in density will lead to a lower tear strength [11]. As of the young modulus, the comparison gives a comparable value in both grades, but it is in contrary to the fact that as the MI increase and a density decrease, it leads to a lower value in young modulus of HDPE-1 [10].

Figure 2. Effect of output rate on (a) Tensile strength properties, and (b) elongation.
Figure 3. Effect of output rate on (a) Tear strength, and (b) Young modulus.

Figure 4. Effect of BUR on impact resistance.

It is acknowledged in figure 6a that the BUR affects several properties like tensile strength at yield and at break. The properties are all corresponded to the molecular orientation and the ability to orient the molecules in more than one direction [11]. As the increase in TD properties is observed,
the MD properties will gradually decrease as some molecules that were initially oriented in MD are now oriented in TD [3]. It also can be seen that HDPE-2 yielded a higher value in tensile strength both at yield and at break as the increase of density will result in a higher value, in contrary to the elongation which be lower because the elongation at break tends to respond in the opposite manner to the tensile strength based on figure 6b [10].

A low blow-up ratio will impart molecular orientation in the machine direction and can lead to bubble instability, but the excessive blow-up ratio is not desirable from the viewpoint of maintaining the bubble stability [9]. Also, a larger BUR over a given die gave a thinner gauge film and greater film width at constant take-off [13]. When an ideal BUR cannot be established due to the reasons of available lay-flat film width, adjustments should be made either with the take-up speed and or the frost line height [10].

3.3. Effect of neck-point height (NPH)
Increasing the neck point height will be affected by adjusting the blower valve and maintaining the bubble stability in BFM [2]. In this experiment, 5 NPH variations i.e. 20; 25; 30; 35; and 40 cm were implemented. When the necking point height is raised, a melted film in aired zone is blown suddenly to frost line zone. As a result, it causes a sharp neck down [14]. NPH needs to be adjusted purposefully to change some mechanical properties of film, such as tear strength, tensile strength, and impact resistance [13]. It is considered that the higher the NPH, the higher the film impact and dart impact as seen in figure 7. The comparison between HDPE-1 and HDPE-2 exhibits a higher value in HDPE-1 as the increase in density will lead to a lower value in film impact property [10].
Figure 6. Effect of BUR on (a) tensile strength and (b) elongation at break.

Figure 7. Impact resistance as the effect of NPH.

The effect of NPH in tensile properties as seen in figure 8a gives a better tensile strength at yield and at break in TD and lower tensile strength at yield and at break in MD as the NPH increased, whilst, elongation at break also tends to respond in the opposite manner compared to tensile strength based on figure 8b [11]. A high neck-point height enables the polymer to achieve a balance of film properties by imparting more bi-axial molecular orientation in the film in TD to match the MD orientation [14].
HDPE-2 exhibits higher value in the tensile strength at yield and tensile strength at break as the density increases. While HDPE-1 exhibits a higher value in elongation at break due to its lower density [10].

In figure 9, the tear strength is found to increase in the MD and decrease in TD with the increasing of NPH, the same thing happened to tensile properties. HDPE-1 exhibits a higher value in tear strength compared to HDPE-2 as the density increases [10].

Figure 8. (a) Tensile strength and (b) elongation at break as the effect of NPH.

Figure 9. Effect of NPH on (a) tear strength and (b) Young modulus.
These 5 variations of NPH exhibit a higher young modulus in both directions as the NPH increased [12]. High NPH allows more time for a film to cool before it reaches the region where the bubble suddenly blown out to its maximum diameter. When it reaches the top stalk will greatly increase the amount of crystallinity and its elasticity [14]. However, since higher NPH tends to reduce other TD properties, sufficient care must be exercised not to raise the NPH too high [10]. In addition, too high NPH may cause the film to stick when it rolled up leading to problems in film gauge control and create a non-uniformity [13].

4. Conclusion
HDPE film was successfully fabricated by using blown film machine with several critical extrusion parameters (output rate, BUR, and NPH) to obtain the optimum film fabricating conditions. These critical extrusion process have affected the film’s orientation balance, the bubble shape, relaxation, and crystallization effects. Therefore, yielded a huge difference in mechanical properties. The differences in operating conditions showed that the higher output makes the process difficult to maintain the orientation balance and decreases the tear and tensile in TD direction, higher BUR makes it hard to maintain bubble stability and decreases several aspects in the MD direction, and higher NPH affect the bubble shape and gradually decrease the strength of the film in the TD direction. The optimum operating condition for HDPE film deends on which mechanical properties required to be achieved by film fabricators.

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