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Analysis of the Effect of Die Angle Variation on the Behavior of Temperature Profile in Extrusion Process by using ANSYS Poly Flow Software

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ABSTRACT

This project is focused on achieving the optimum die angle and volumetric flow rate for extrusion process. In extrusion process, the temperature of the melt might get increased at the die exit, due to the friction between melt and the die surface, which leads to the degradation of plastic material properties. So the basic aim of this project is to control the melt temperature by governing different factors responsible for the rise of temperature. When the plastics melt enters the axis-symmetric steel die at a given temperature and at a given flow rate and passes through it, during the process heat generation takes place due to viscous dissipation. The increase in temperature of the melt occurs due to the shearing taking place in the die. The amount of temperature increased during the process can be controlled by changing the die angle and the volumetric flow rate of the plastic melt.

The 2-d model and the meshing for this work is generated in GAMBIT software, Whereas the overall simulation is performed on Polyflow module of ANSYS software.

***Keywords*--** ANSYS, CFD, Die Angle, Extrusion, GAMBIT

I. INTRODUCTION

Extrusion is the process of confining the plastic material in a closed cavity and then allowing it to flow from only opening so that it will take the shape of the opening. Extrusion equipment consists of a plasticizing extruder, die assembly, a cooling assembly, and haul-off or winding equipment. Extrusion is a continuous process, as opposed to molding, which is a cyclic process. Extrusion is suitable for many types of continuous plastic products that have a uniform outside shape and can be coiled, cut, or wound. The transformation of a solid plastic feedstock material into a molten viscous fluid takes place in the extruder barrel, through the mechanical shearing action of a rotating screw and the heat provided by electrical resistance heaters clamped to the outside of the extruder barrel and die. The combination of the mechanical, rotating shearing action of the screw and the heat of the electrical heaters causes the solid plastic feedstock to change into a hot molten material.

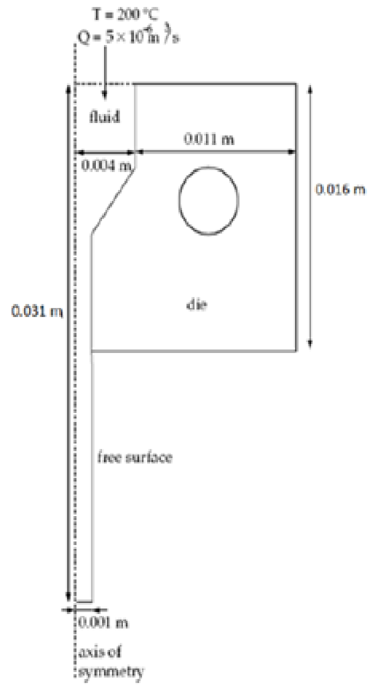
The quality of the product produced in extrusion process depends on so many factors like Die design, cooling technique used for the product, volume flow rate etc. The temperature of the melt increases due to viscous dissipation caused by the shearing taking place in the die. The temperature of the fluidis critical for the process. The viscosity of the fluid changes with temperature, which leads to the modification of the shape of the extrudate. The polymer might degrade if the temperature is too high, so a numerical simulation is of great interest to optimize the operating conditions.

Temperature of the plastics melt rises inside the die due to shearing and this can be controlled by optimizing die angle and the volume flow rate.

II. METHODOLOGY

First of all, we do theoretical and practical survey to identify faults in components produced by extrusion. By doing so we get to know that the dimension of the component is varying as well as the properties of plastics is degrading to some extent. Different factors are taken in to account which are responsible for the quality of the product, and among these factors we have considered die angle and volume flow rate are the crucial factors which plays important role in governing the quality of the product.

2.1



Geometrical Modeling and Meshing

Modeling of 2D axis-symmetric die is done on GAMBIT.

In modeling process, to reduce the time required for simulation we have created 2D axis-symmetric die. Map type meshing process have been adopted, so that we can get uniform meshing throughout the die.

2.2 Simulation(CFD Analysis)

Computer based simulation is performed on poly-flow module of ANSYS software to optimize the die angle and mass flow rate. Several different simulations are being performed with different die angles and mass flow rate, so that we know its effect on the temperature difference developed during the process.

2.3Validation

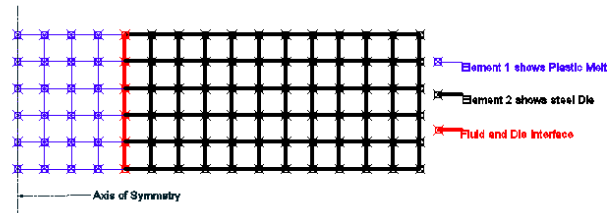
The results shown in ANSYS are then validated by doing numerical calculation through Mathematical Model.

2.4 Mathematical Modeling

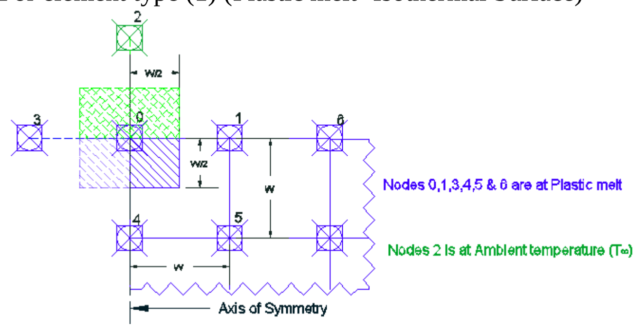
Then we have created a mathematical model to calculate the temperature change at the exit of the Die by using 2-D heat balancing equations (through both conduction and convection), heat loss formulation via viscous friction (due to decreasing flow diameter) and also by using Finite element concepts. The data taken for calculation is considered to be standard data. For calculation purpose parameters like dimensions of the die, plastics material properties, temperature of melt at the inlet and the die material is selected.

We have divided the problem into three domains:

Domain-1: For Cylindrical axis-symmetric portion



For element type (1) (Plastic melt -Isothermal Surface)



Applying the heat balance equation for node '0'

$$Q_{1-0} + Q_{2-0} + Q_{3-0} + Q_{4-0} = 0$$

$$k_f \times \left(\frac{w}{2}.1\right) \times \frac{(T_1 - T_0)}{w} + h_{a_f} \times (w.1) \times (T_\infty - T_0) + k_f \times \left(\frac{w}{2}.1\right) \times \frac{(T_3 - T_0)}{w} + k_f \times (w.1) \times \frac{(T_4 - T_0)}{w} = 0$$

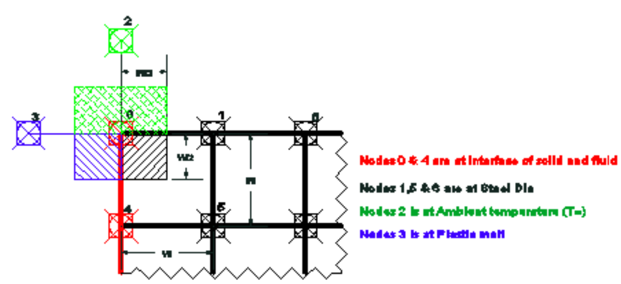
Now, applying the heat balance equation for node '1'

$$Q_{2-1} + Q_{0-1} + Q_{6-1} + Q_{5-1} = 0$$

$$h_{a_f} \times (w.1) \times (T_\infty - T_1) + k_f \times \left(\frac{w}{2}.1\right) \times \frac{(T_0 - T_1)}{w} + k_f \times \left(\frac{w}{2}.1\right) \times \frac{(T_6 - T_1)}{w} + k_f \times (w.1) \times \frac{(T_5 - T_1)}{w} = 0$$

The above two equations clarifies how the further more equations for several nodes can be structured.

For the element type (2) (Steel Die)



Applying the heat balance equation for node '0'

$$Q_{1-0} + Q_{2-0} + Q_{3-0} + Q_{4-0} = 0$$

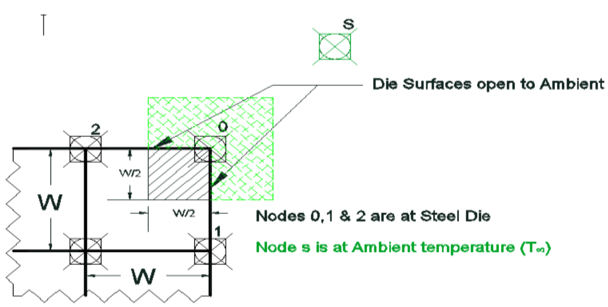
$$k_d \times \left(\frac{w}{2}.1\right) \times \frac{(T_1 - T_0)}{w} + \left(h_{a_f} + h_{a_d}\right) \times \left(\frac{w}{2}.1\right) \times (T_\infty - T_0) + k_f \times \left(\frac{w}{2}.1\right) \times \frac{(T_3 - T_0)}{w} + h_f \times \left(\frac{w}{2}.1\right) \times (T_3 - T_0) + \left(k_f + k_d\right) \times \left(\frac{w}{2}.1\right) \times \frac{(T_4 - T_0)}{w} = 0$$

Now, applying the heat balance equation for node ‘1’

$$Q_{2-1} + Q_{0-1} + Q_{6-1} + Q_{5-1} = 0$$

$$h_{a_d} \times (w.1) \times (T_\infty - T_1) + k_d \times \left(\frac{w}{2}.1\right) \times \frac{(T_0 - T_1)}{w} + k_d \times \left(\frac{w}{2}.1\right) \times \frac{(T_6 - T_1)}{w} + k_d \times (w.1) \times \frac{(T_5 - T_1)}{w} = 0$$

For corner node points of the die

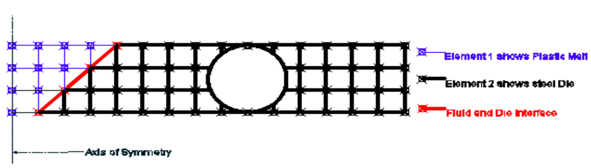


Applying the heat balance equation for node ‘0’

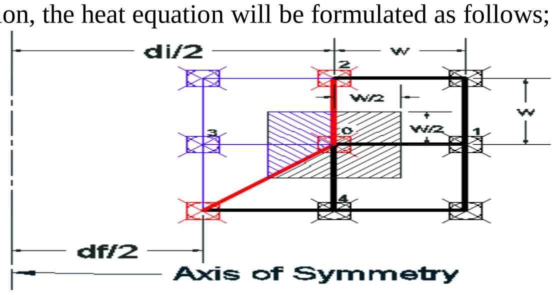
$$Q_{1-0} + Q_{2-0} + Q_{s-0} = 0$$

$$k_d \times \left(\frac{w}{2}.1\right) \times \frac{(T_1 - T_0)}{w} + k_d \times \left(\frac{w}{2}.1\right) \times \frac{(T_2 - T_0)}{w} + h_{a_d} \times (w.1) \times (T_\infty - T_0) = 0$$

Domain-2: For Frustum axis-symmetric portion



For node points of Plastic melt and Steel die portions, the procedure to construct the equations is same. But at the intersection of the node points of fluid and die portion, the heat equation will be formulated as follows;

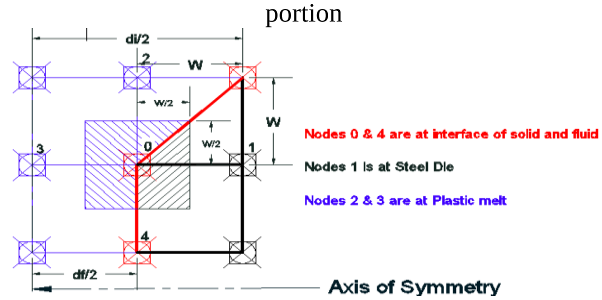


Applying the heat balance equation for node ‘0’

$$Q_{1-0} + Q_{2-0} + Q_{3-0} + Q_{4-0} + \dot{W}_f = 0$$

$$k_d \times (w.1) \times \frac{(T_1 - T_0)}{w} + \left(k_d + k_f\right) \times \left(\frac{w}{2}.1\right) \times \frac{(T_2 - T_0)}{w} + \left(k_f \times \left(\frac{3w}{4}.1\right) + k_d \times \left(\frac{w}{4}.1\right)\right) \times \frac{(T_3 - T_0)}{w} + h_f \times \left(\left(\frac{w}{2} + \frac{w}{\sqrt{2}}\right).1\right) \times (T_3 - T_0) + \left(k_d \times \left(\frac{3w}{4}.1\right) + k_f \times \left(\frac{w}{4}.1\right)\right) \times \frac{(T_4 - T_0)}{w} + \frac{\pi}{\sqrt{3}} \sigma_y d_i^2 V_i \ln\left(\frac{d_i}{d_f}\right) = 0$$

Domain-3: For the extruding cylindrical axis-symmetric portion

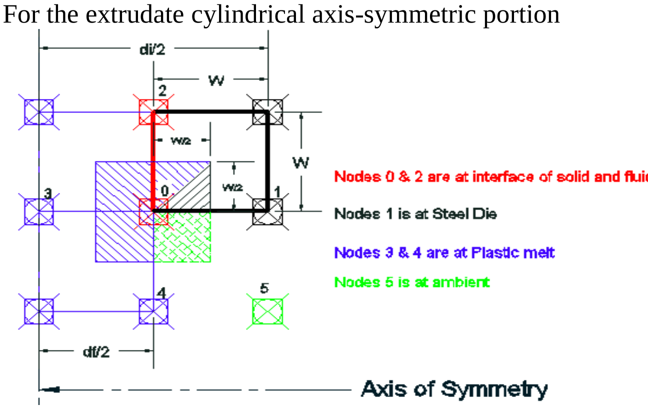


Applying the heat balance equation for node ‘0’

$$Q_{1-0} + Q_{2-0} + Q_{3-0} + Q_{4-0} + Q_{s-0} + \dot{W}_f = 0$$

$$\left(k_d \times \left(\frac{3w}{4}.1\right) + k_f \times \left(\frac{w}{4}.1\right)\right) \times \frac{(T_1 - T_0)}{w} + \left(k_f \times \left(\frac{3w}{4}.1\right) + k_d \times \left(\frac{w}{4}.1\right)\right) \times \frac{(T_2 - T_0)}{w} + h_f \times \left(\frac{w}{\sqrt{2}}.1\right) \times (T_2 - T_0) + k_f \times (w.1) \times \frac{(T_3 - T_0)}{w} + \left(k_f + k_d\right) \times \left(\frac{w}{2}.1\right) \times (T_4 - T_0) + \frac{\pi}{\sqrt{3}} \sigma_y d_i^2 V_i \ln\left(\frac{d_i}{d_f}\right) = 0$$

For the extrudate cylindrical axis-symmetric portion



Applying the heat balance equation for node ‘0’

$$Q_{1-0} + Q_{2-0} + Q_{3-0} + Q_{4-0} + Q_{5-0} = 0$$

$$\left(\frac{k_d + k_f}{2}\right) \times \left(\frac{w}{2}.1\right) \times \frac{(T_1 - T_0)}{w} + \left(k_f \times \left(\frac{3w}{4}.1\right) + k_d \times \left(\frac{w}{4}.1\right)\right) \times \frac{(T_2 - T_0)}{w} + k_f \times (w.1) \times \frac{(T_3 - T_0)}{w} + h_f \times \left(\frac{w}{2}.1\right) \times (T_3 - T_0) + k_d \times \left(\frac{w}{2}.1\right) \times \frac{(T_4 - T_0)}{w} + \left(h_{a_f} + h_{a_d}\right) \times \left(\frac{w}{2}.1\right) \times (T_\infty - T_0) = 0$$

III. PRIOR APPROACH

1. Ajiboye & Adeyemi (2006)Studied about the effect of die land length on the extrusion pressure. It was found that extrusion pressure increases with increase in complexity of die geometry, for die length, the extrusion pressure is lowest for square section and highest for rectangular section & for a particular reduction in area extrusion pressure increases with increasing die length and vice versa.
2. Gordon et al (2007) have used the adaptable die design method, in conjunction with upper bound method that allows the rapid evaluation of a large number of die shapes and discovery of the desired die that produces the desired outcome. A double optimization process is used to determine the values for the flexible variables in the velocity field and secondly to determine the die shape that best meet the given criteria.
3. Karol Pepliński, ArkadiuszMozer (2010) was presented the methodology of numerical simulation for the die design. A commercial computer fluid dynamics program Ansys Polyflow was used to design the die passage. The objective is to determine the die passage that results in a balanced mass flow exiting the die that closely matches the target profile. The die land shape modify with using optimization algorithm is very helpful to obtain geometry and dimension of extrudate desired profile.
4. D.Y. Yang, K.J. Kim (2007) have worked on various industrial extrusion problems with high complexity are simulated by employing efficient numerical schemes such as the arbitrary Lagrangian–Eulerian Finite element method and mismatching refinement with the domain decomposition. And a new methodology of shape optimization technique to reduce computation time for the design of the extrusion process is introduced. The mechanical properties like anisotropy of extruded product are analyzed by the continuum approach and discussed for practical examples, and the texture development and mechanical properties in the aluminum extrusion processes are predicted by employing rate independent crystal plasticity model based on the smooth yield surface with rounded-off corners.
5. Patrick Ulysse (1999) have worked on an approximate model has been developed to improve our understanding of flow control at the exit of an extrusion die. He deals with the design of traditional die flow corrector used in flat faced aluminum extrusion dies. The numerical model uses the finite-element method combined with techniques of mathematical programming. Analytical sensitivity has been developed from the discretized finite element equations in order to compute the necessary derivatives during optimization. The model includes thermal effects and the extruded outlet material is assumed to be temperature dependent and strain rate.

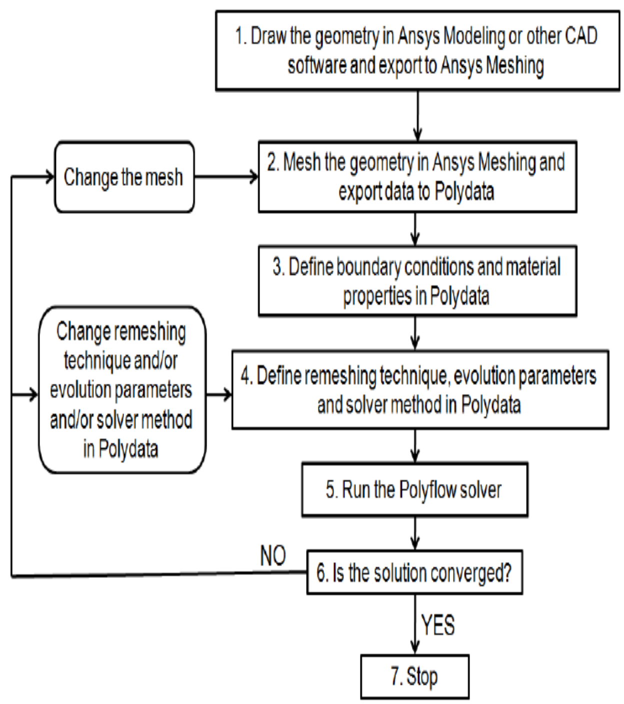


Figure 1: Flowchart for numerical simulation using Ansys Polyflow [Karol Pepliński, ArkadiuszMozer (2010)]

In all the above research works, authors have done their research work on identifying the effect of die land length on the extrusion pressure or the other have worked on the die design to get desired shape of the product but they have not worked on optimizing the die angle or mass flow rate to control the temperature of the product at the die exit. Appropriate die angle and mass flow rate can help us to achieve desired shape and size of the product. Moreover, by controlling the temperature of the meltat die exit we can improve the quality of the product because the higher temperature may leads to degradation of material properties.

Secondly, there is need to validate the results shown in ANSYS or any other software. Validation can be done in many ways either we can perform the same analysis in two different software with the same input values, or we can validate our results through numerical calculation on the basis mathematical model.

By studying above projects we found some deficiencies and there is scope to do some further works. So we have chosen to do optimization of die angle and mass flow rate to improve the quality of the product. This will be done on the basis of maximum temperature achieved by the melt near the die exit or we can say on the basis of rise of temperature of the material which is in direct contact of the die wall during extrusion process.

IV. OUR APPROACH

This is a coupled problem of non-isothermal flow of a fluid and heat conduction in an axis-symmetric steel die.

When the plastics melt enters the axis-symmetric steel die at a given temperature and at a given flow rate and passes through it, during the process heat generation takes place due to viscous dissipation. The increase in temperature of the melt occurs due to the shearing taking place in the die. The temperature of the fluid is critical for the process as the polymer might degrade if the temperature is too high. The viscosity of the fluid changes with temperature, which leads to the modification of the shape of the extrudate. The problem involves flow, heat transfer by conduction and convection, and heat generation by viscous dissipation. Energy momentum and incompressibility equations are solved in the fluid domain. The energy equation for heat transport problems is solved in the solid (die) domain.

So a numerical simulation is of great interest to optimize the operating conditions. Moreover, the die angle and the volumetric flow rate are having direct impact on shearing rate of plastics melt.

Aim: - As this is a coupled problem of non-isothermal flow of a fluid and heat conduction ina axis-symmetric steel die. For simulation purpose we are taking standard values for the parameters like melt temperature, volumetric flow rate, and dimensions of die. Then further we will vary the die angle and the volumetric flow rate to observe its effect on the melt temperature and local shearing. Our aim is to design the die with optimum angle and to select optimum volumetric flow rate which will results in minimum rise of melt temperature.

Geometry Building and Meshing-

Geometry is created in the GAMBIT software. Standard Die dimensions and parameters are selected and the same values will be taken for validation purpose.

TABLE I

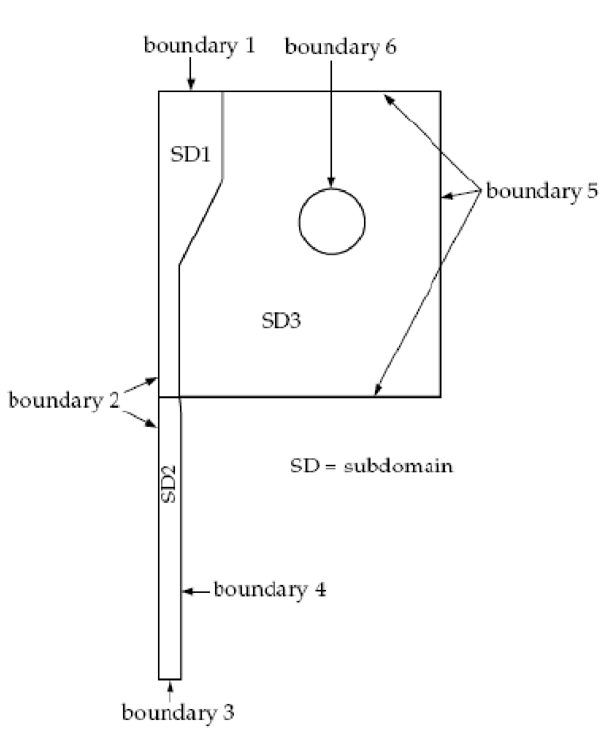
SYMBOLIC ABBREVIATION

Symbol	Quantity
n_0	zero shear rate
$\dot{\gamma}$	shear rate
M	Bird-Carreau law index
Λ	natural time
T_α	Reference temperature
T & T_0	Absolute temperature
v_n	Zero surface normal velocity
f_s	zero tangential force
T	Shear stress
M	Dynamic viscosity
U	Flow velocity
Y	height above the boundary
Q_{a-b}	Heat flow from node 'a' to 'b'
k_d	Conductive heat transfer co-efficient in Steel Die
k_f	Conductive heat transfer co-efficient in Plastic melt
h_f	Convective heat transfer co-efficient between Plastic melt and steel die.
h_{a_d}	Convective heat transfer co-efficient between ambient and steel die.
h_{a_f}	Convective heat transfer co-efficient between ambient and plastic melt
w	Width & height of mesh element
d_i	Initial diameter of plastic melt
d_f	final diameter of plastic melt
$\dot{W}_f$	Frictional (viscous) heat loss

Boundaries and Sub-Domains selection

The most important step of CFD analysis is to define the sub-domains and boundary conditions of the geometry.

- SD1 is for molten plastic material and this is a fluid domain.
- SD2 is for extrudate and this is also a fluid domain.
- SD3 is for solid die and this is a solid domain.



- Boundary 1 is for inlet
- Boundary 2 is for axis-symmetric line
- Boundary 3 is for outlet
- Boundary 4 is for extrudate free surface
- Boundary 5 is for die surface
- Boundary 6 is for hole internal surface

After creating the geometry and defining boundary condition meshing process is done. Basically Mapped mesh option is used to generate uniform mesh throughout the surface of the geometry.

Then the file is saved in .msh format, so that to import in ANSYS (Poly flow). Different steps followed in Poly Flow to perform analysis are as follows:-

1. Project and Mesh- Import .msh file in PolyFlow
2. Definition of Models, Materials, and Boundary Conditions
3. Definition of the Fluid Sub-Task

- Generalized Newtonian non-isothermal flow problem
- Shear-rate dependence of viscosity

Viscosity is defined by the *Bird-Carreaulaw* as

$$F(\dot{\gamma}) = n_0 \left[1 + (\lambda\dot{\gamma})^2\right]^{\frac{m-1}{2}}$$

- Temperature dependence of viscosity

For this problem, we have assumed that the dependence of viscosity on temperature follows the *Arrhenius law.*

The Arrhenius law is given as: -

$$H(T) = \exp\left[\alpha\left(\frac{1}{T - T_0}\right) - \alpha\left(\frac{1}{T_\alpha - T_0}\right)\right]$$

- Flow boundary conditions
- Thermal boundary conditions

1. Definition of the Fluid Sub-Task
   - Material data
   - Thermal boundary conditions
2. Defining Numerical Parameters
3. Outputs setting

V. RESULTS

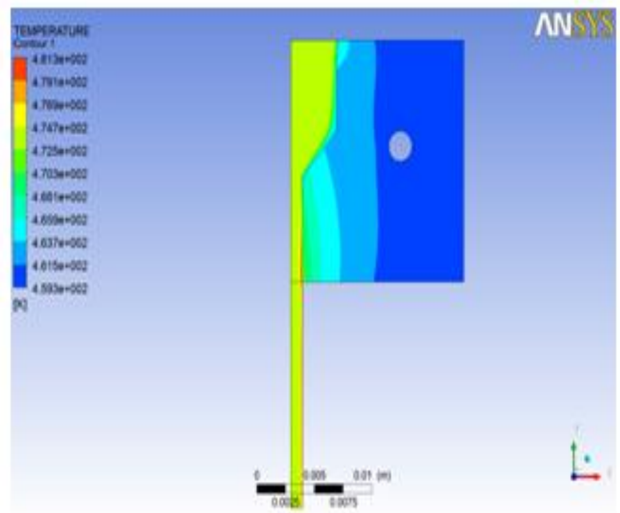


Fig-1 Temperature contour for the base model(Standard Dimensions)

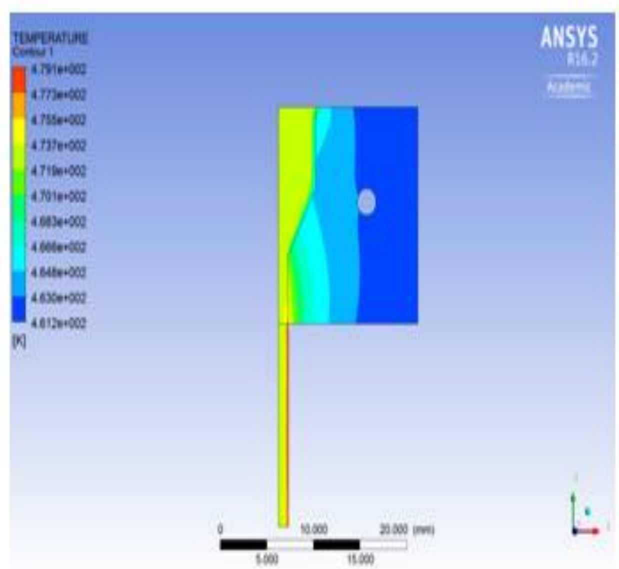


Fig-2 Temperature contour for the 2nd trail(Decreased Die angle)

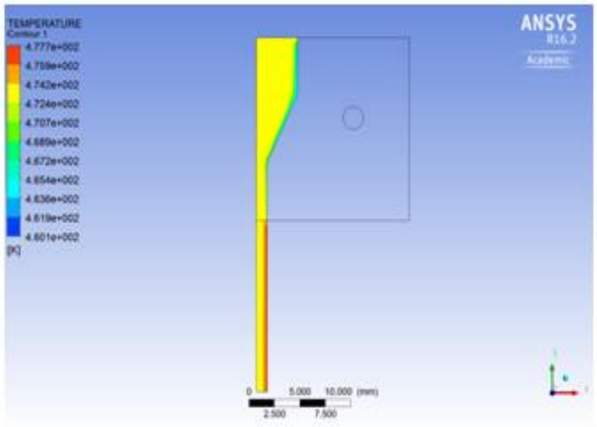


Fig-3 Temperature contour for the 3rd trail(Further Decreased Die angle)

The above figure shows us the effect of change in die angle on the temperature of the plastics melt while flowing through die. Our aim is to compare the variation of die angle with different intrinsic parameters like temperature, pressure, velocity, etc without changing the other physical and mechanical properties of Plastic Melt such as initial and final cross sectional area, discharge, entrance temperature, die temperature, etc.

1st Case-In the first case, As we can see in the Fig-1 the maximum temperature contour is shown at the exit location of the die and that is about 481.3 Kelvin, this is because of the surface friction between die internal wall (flow way) and the fluid. When the plastics melt enters steel die its temperature is molding temperature (470K) but when it exits the die the melt temperature rise to the maximum temperature of 481.3 K. This heat generation takes place due to viscous dissipation.

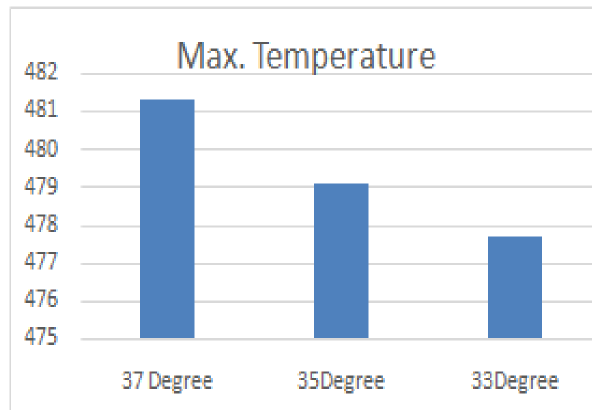
Moreover we can observe slight inflation of the extruded surfaces at the exit location of the die. The reason behind inflation is rise in melt temperature.

2nd Case–In second case(Fig-2)we have decreased the die angle by2^{o}. The maximum temperature obtained at exit is 479^{o}Kelvin and this is significantly less than the prior analysis. This shows us the temperature will get reduced on decreasing Die angle. This is due to resistance in the fluid flow reduces. Thus heat generation further reduces. So temperature in the fluid gets reduced.

3rd Case – In this case, (Fig-3) also we have further reduced the die angle by 2^{o}. From the image we can easily observe that the maximum temperature 477^{o} Kelvin is much less in compare to prior cases. This is due to the fact that the friction between the fluid particles and the die surfaces reduces on reducing the die angle. Reduction in friction leads to the reduction in heat generation.

VI. CONCLUSION

On the basis of above results, a relationship is established between the die angle and rise in the temperature of plastic melt adjacent to die wall. And we can conclude that by decreasing the Die Angle the frictional resistance get reduced which results in decrease of maximum temperature. Through the table given below we can see that if we reduce the Die Angle, the maximum temperature near the Die walls decreases.



Temperature comparison chart of analysis done on Dies with different die Angles

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