

Estimation of Filament Temperature in Spinning Line and Modelling of Fibre Formation

S. S. Bhattacharya¹, D.K. Sullere²

Professor, Dept. of Textile Engineering, Faculty of Engineering & Technology, M.S. university, Vadodara, Gujarat, India¹

Principal, M.S. Polytechnic, Surat, Gujarat, India²

ABSTRACT: In this paper a relation of spinning threads line temperature at any distance from spinneret for given air quantity, quench air temperature and throughput per filament is derived. Nusselt number of the quench air is calculated with the help of Reynolds and Prandtl numbers. A relation between filament temperature with quench air temperature and melt temperature is derived by applying heat balance equation considering filament volume element. We can also modify our quench air system and change quench air parameters best suitable to our titre plan and specially denier per filament and type of polymer also.

KEYWORDS: Heat Balance, Specific Heat, Heat Transfer Co-Efficient, Filament Temperature, Nusselt Number, Reynolds Number.

I. INTRODUCTION

Air quench chambers are means of cooling and solidifying melt spun filaments bundles coming out from spinneret bores for winding in a few meters distance¹. Within this range, the filaments are formed from the liquid phase with very low strength and receive their geometrical properties, the pre orientation of the macro molecules and other properties such as uniform dyability, crystallinity, elongation and tenacity, young's modulus, etc., which are subjected to high and consistently rising standard requirements.

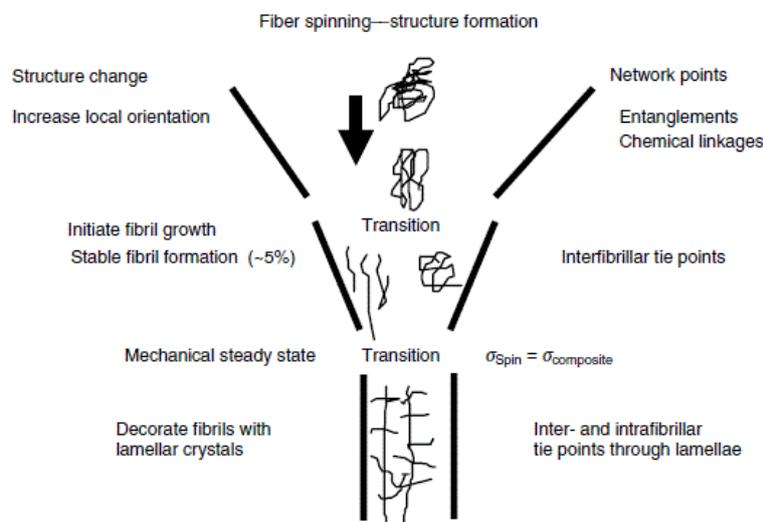


Figure 1: Fibre structure formation²

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Proper rate of quenching of the filament, laminar flow of quench air and steady thread line in spinning are the most important aspects of a good quenching system in melt spinning process. The main aim of quenching is to dissipate the heat of molten polymer melt and bring down the temperature of the filaments below glass transition temperature (T_G) before winding the yarn at take-up.

Between the spinneret and the take-up mechanism the yarn path can be divided into three zones:

- ⇒ The drawing of the melt from the spinneret hole at a melt temperature T and draw viscosity P_s ,
- ⇒ The draw zone with filament cooling to the solidification temperature and then further to below the glass transition temperature,
- ⇒ The arrival at the first solid or take-up mechanism where the temperature should be less than the glass transition temperature.

So, the rates of cooling and thread line temperature are very important factors as fibre formation takes place up to the point where filament temperature is above glass transition temperature of polymer. It is known that molecular chains mobility stops at temperature below T_G and thus drawing become difficult.

II. PRINCIPLES OF MELT SPINNING AND QUENCHING

A. Rheological Equations of State ^(3,4,5)

At times some polymers appear to behave very much like “conventional” solids, at other times like liquids. Sometimes, such as when they are rubbery, they have at the same time the characteristics of both solids and liquids. In fact, most polymers have at some time or other the characteristics both of elastic solids and viscous liquids. For such materials we often use the term Viscoelastic. In recent years this term has sometimes been restricted to materials that are essentially elastic solids but which show viscous overtones. The studies of dynamic properties and creep behaviour, so important to the usage of rubbers and plastic, are mainly concerned with such Viscoelastic behaviour. Following equation gives the how shear stress is related to shear strain.

$$\sigma(x) \propto \frac{d}{dx} v(x)$$

$$\sigma(x) = \mu(x) \cdot \frac{d}{dx} v(x) \quad \dots\dots\dots(I)$$

Where, $\sigma(x)$ = shear stress,

$\frac{d}{dx} v(x)$ = rate of the deformation,

$\mu(x)$ = viscosity.

B. General features of Melt Spinning

Formation⁶ of filament after the melt spinning procedure involves preparation of spinning fluid (by melting of a solid fibre forming material), extrusion of the melt through spinneret's into a cooling chamber and winding of the resulting filaments on to spools or bobbins (Fig. 2) Spinning melt is extruded at constant temperature to constant mass rate w , which together with the diameter of spinneret orifice d_o , and material density ρ , determines the extrusion velocity v_0 . The take- up device mounted at distance L , from spinneret gives the filament constant velocity V_L , related to the average diameter of spun filament d_L . Along the spinning path, i.e. between the extrusion (x_0) and take-up positions (x_L) the fluid jet is deformed, cooled, solidified and transformed into a filament with a super molecular texture.

Solidification in melt spinning is due exclusively to heat transfer. The rate and cooling process is sometimes controlled by transverses air blow. Materials with very long relaxation times and low spin ability, (high-molecular polyolefin's)

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Vol. 4, Issue 12, December 2015

are often spun into heat celled to reduce the cooling and solidification rates. On the other hand, thick bristles are spun into liquid baths (water) where heat transfer is very rapid.

Spinning velocities V_L , used in melt spinning range from 1000 meters/minute (thick mono filaments in liquid baths) to several thousand meters/minute though filament in gases medium. High spinning velocities, the lack of auxiliary materials (solvents, precipitators, etc) and the simplicity of spinning apparatus, make melt spinning the most convenient and economic method of fibre manufacture. The only limitation of the method is due to the fibre-forming material which must be fusible and yield thermally stable spinneret melts.

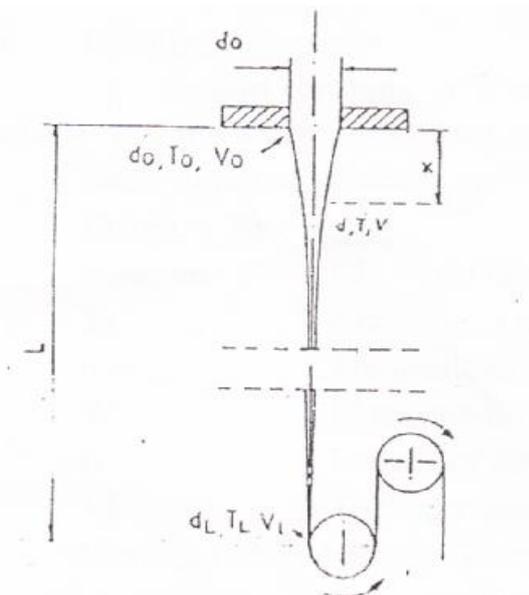


Figure 2: Schematic diagram of PET melt spinning

Therefore the condition of continuity in a steady state reads –

$$\rho(x)V(x)A(x)=w \text{ Constant} \dots\dots\dots(\text{II})$$

Where, ‘A’ and ‘V’ are the cross section area and average axial velocity of the spinning line, and ‘ ρ ’ is the material density, all taken at a distance ‘x’ from the spinneret.

C. TYPES OF COOLING WITH QUENCH AIR ⁽⁷⁾

Normally the types of cooling are used to quench thermoplastic polymers produced through melt spinning:

- i. Cross air flow
- ii. Radial air flow (in flow & outflow type) as shown in fig. No. 3(a & b)

Most common type is cross quench air flow or transverse flow. But limitation that in this type only 25% of air could be used for the purpose of quenching and rest 75% goes as waste.

Where as radial quench air type is best suitable to produce staple fibres where the numbers of ends are very high. In this type of air flows utilisation of air up to 70%.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

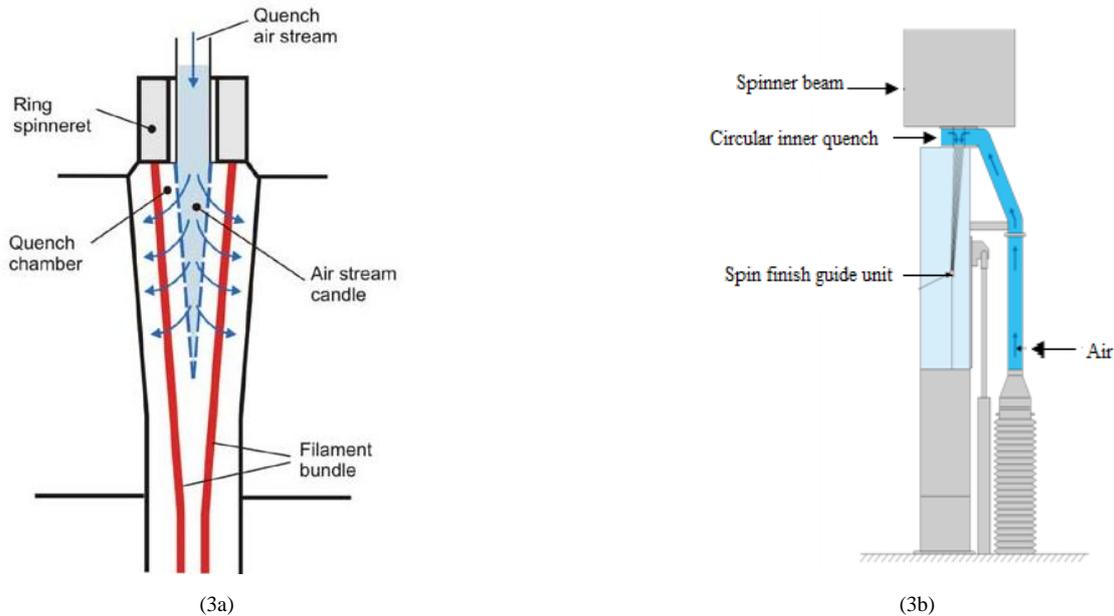


Figure 2: a) CIQ (Circular Inflow Quench) system⁸
b) COQ (Circular outflow quench) system⁸

D. Quench air flow around and in a spinning multi filament bundle.

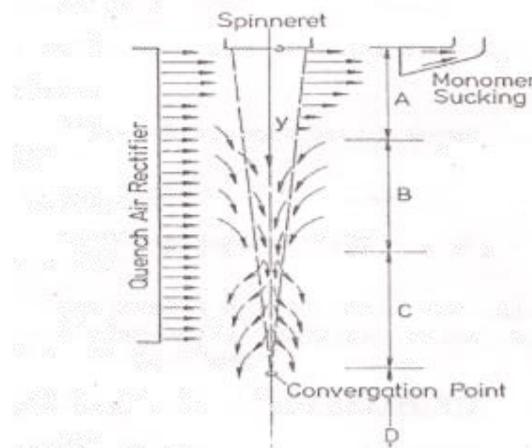


Figure 4: Quench air flow⁽⁷⁾

- Zone A — cross flowing passing quench air caused by low individual filament speed.
- Zone B — Quench air sucked in by a filament bundle.
- Zone C — Quench air pressed out of a filament bundle by multi filament convergence.
- Zone C/D -Convergence points made for example by an oiler pins and/or thread guide.
- Zone D — Close filament bundle up to the take-up machine.

Today, short cooling times are normal for textile yarn, even for nylon-6 carpet yarn with approx 20 dtex POY spin titre, 0.4 s cooling time are possible. Poly-propylene only makes an exception as its inner heat conductivity is much lower than that of PA or PES.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

III. MODELLING OF FIBRE FORMATION

To derive a relation of filament temperature for a given quench air temperature, melt temperature of polymer, Nusselt number, heat transfer co-efficient from filament surface to surrounding air, quantity of melt per filament and specific heat of polymer, we have to calculate quantity of melt per filament, filament diameter and Nusselt number for the system.

A. Calculation of quantity of melt per filament

(I) For denier 126/36 PET

For this denier per filament comes out 3.5 denier.

Mass of 1 meter of single filament of 3.5 denier = $3.5 / 9000$ gms

For take-up speed 3200m/minute, quantity in Kg/sec/filament = $(3.5 * 3200 * 10^{-3}) / (9000 * 60)$
= $0.0207 * 10^{-3}$

(II) Similarly mass of one filament for 240/12 denier

At 3500m/minutes comes out = $(3500 * 240 * 10^{-3}) / (9000 * 12 * 60)$ kg/sec/hole
= $0.129 * 10^{-3}$ kg/sec/hole

B. Calculation of diameter of single filament⁹

We know, Diameter (D) in microns = $11.89 * \sqrt{d/\rho}$, Where 11.89 is constant factor, d = denier per filament
 ρ = Average density of yarn in grams/cm³

Therefore diameter of single filament for 126/36 PET yarn = $11.89 * \sqrt{3.5/1.38}$
= 18.93 micron
= $18.93 * 10^{-6}$ meters

Similarly diameter of single filament of 240/12 PET yarn = $11.89 * \sqrt{20/1.38}$
= 45.42 micron
= $45.42 * 10^{-6}$ meters

C. Calculation of Nusselt number of quench air at 20⁰C

In heat transfer at a boundary (surface) within a fluid, the Nusselt number (Nu) is the ratio of convective to conductive heat transfer across (normal to) the boundary. In this context, convection includes both advection and diffusion. Named after Wilhelm Nusselt, it is a dimensionless number. The conductive component is measured under the same conditions as the heat convection but with a (hypothetically) stagnant (or motionless) fluid. A similar non-dimensional parameter is Biot Number, with the difference that the thermal conductivity is of the solid body and not the fluid¹⁰.

$$Nu_L = \frac{\text{Convective heat transfer}}{\text{Conductive heat transfer}} = \frac{hL}{k}$$

Where, Nu_L = nusselt number

h = co-efficient of heat transfer from filament surface to surrounding air

L = characteristics length

K = Heat conductivity of air

The Reynolds number is defined as the ratio of momentum forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions.

$$Re = \frac{\text{Inertial force}}{\text{Viscous force}} = \frac{\rho V L}{\mu} = \frac{V L}{\nu}$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

where:

- V is the maximum velocity of the object relative to the fluid (SI units: m/s)
- L is a characteristic linear dimension, (travelled length of the fluid; hydraulic diameter when dealing with river systems) (m)
- μ is the dynamic viscosity of the fluid (Pa·s or N·s/m² or kg/(m·s))
- ν is the kinematic viscosity ($\nu = \frac{\mu}{\rho}$) (m²/s)
- ρ is the density of the fluid (kg/m³).

Prandtl number is defined as the ratio of momentum diffusivity to thermal diffusivity. That is, the Prandtl number is given as¹⁰:

$$Pr = \frac{\nu}{\alpha} = \frac{\text{viscous diffusion rate}}{\text{thermal diffusion rate}} = \frac{c_p \mu}{k}$$

where:

- ν : momentum diffusivity (kinematic viscosity), $\nu = \mu/\rho$, (SI units: m²/s)
- α : thermal diffusivity, $\alpha = k/(\rho c_p)$, (SI units: m²/s)
- μ : dynamic viscosity, (SI units: Pa s = N s/m²)
- k : thermal conductivity, (SI units: W/m-K)
- c_p : specific heat, (SI units: J/kg-K)
- ρ : Density, (SI units: kg/m³).

We know Nusselt number is a function of Reynold's numbers and Prandtl number

$$N_u = f(R_e, Pr)$$

$R_e = D V/\nu$ where, D is diameter, V = velocity of fluid and ν is kinematic viscosity of fluid

$$\begin{aligned} R_e \text{ of quench air } 20^{\circ}\text{C for } 126/36 \text{ polyester yarn} &= D V/\nu, \text{ (where, D (diameter of single filament of } 3.5 \text{ denier)} = \\ &18.93 * 10^{-6} \text{ meter, V(velocity of air)} = 0.5 \text{ m/s and } \nu = 15.077 * 10^{-6} \text{ m}^2/\text{s}) \\ &= 18.93 * 10^{-6} * 0.5 / 15.077 * 10^{-6} \\ &= 0.63 \end{aligned}$$

$Pr = C_p \mu/K$ where, C_p = specific heat of air in Kjoule/kg.⁰C , μ = dynamic viscosity of air kg/m.s and K= Heat conductivity of air watt/meter.⁰C

$$\begin{aligned} Pr \text{ number of air (at } 20^{\circ}\text{C)} &= C_p \mu/K \\ &= 1005.6 * 1.8116 * 10^{-5} / 0.026 \\ &= 0.70 \end{aligned}$$

Now, for this range of Reynold's numbers and Prandtl number we can use the relation given by Hilpert¹¹

$$\begin{aligned} N_u = h*d/k &= CR_e^m Pr^{1/3}, \text{ Where } C = 0.99 \text{ and } m = 0.33 \text{ are constant of this equation for circular cylinder in cross flow} \\ N_u \text{ (of quench air at } 20^{\circ}\text{C)} &= 0.99 * 0.63^{0.33} * 0.70^{0.33} \\ &= 0.99 * 0.8585 * 0.89 \end{aligned}$$

N_u (of quench air at 20⁰C) = 0.756 of quench air for 126/36 (single filament denier is 3.5) PET yarn

Similarly,

$$\begin{aligned} R_e \text{ of quench air } 20^{\circ}\text{C for } 240/12 \text{ PET yarn} &= DV/\nu, \text{ (Where, D(diameter of single filament of } 20 \text{ denier)} = 45.43 * 10^{-6} \\ &\text{meter, V(velocity of air)} = 0.5 \text{ m/s and } \nu = 15.077 * 10^{-6} \text{ m}^2/\text{s}) \\ R_e &= 45.43 * 10^{-6} * 0.5 / 15.077 * 10^{-6} \\ &= 1.5065 \end{aligned}$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

$$Pr \text{ number of air (at } 20^{\circ}\text{C)} = C_p \mu / K$$

$$= 1005.6 * 1.8116 * 10^{-5} / 0.026$$

$$= 0.70$$

Now, for this range of Reynold's numbers and Prandt number we can use the relation given by Hilpert $Nu = h*d/k = CR_e^m Pr^{1/3}$, Where $C = 0.989$ and $m = 0.33$ are constant of this equation for circular cylinder in cross flow Nu (of quench air at 20°C) = $0.99 * 1.5065^{0.33} * 0.70^{0.33}$
= $0.99 * 1.144 * 0.89$

Nu (of quench air at 20°C) = 1.008 of quench air for 240/12 (single filament denier is 20) PET yarn

D. Derivation of filament temperature at x meter distance from the spinneret

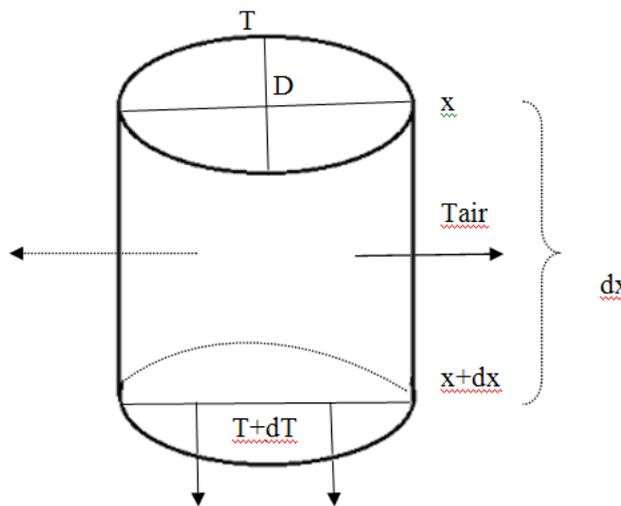


Figure 4 : Heat flow balance of a filament volume elements¹²

Simplified analysis

If we at first assumed only heat convection (i.e. no heat conduction and no heat sources within filaments, no heat radiation), than heat balance of any volume element between x and $x+dx$ is given by the following equation. The difference in heat flow into the unit volume that is the heat transfer from the surface of the unit volume into the surrounding air (fig.4) .

The heat balance equation can be written as

$$Q * C_p * (T) - Q * C_p * (T+dT) = h * (T - T_{air}) * \pi * D * dx \dots\dots\dots(III)$$

and

$$Nu \text{ (Nusselt no.)} = h * D / k_{air} \dots\dots\dots(IV)$$

Where, Q = Polymer throughput

C_p = A specific heat of polymer

k_{air} = Heat conductivity of air

h = Heat transfer co-efficient from the filament surface to surrounding air from equation (III) and (IV)

$$Q * C_p * (T - T - dT) = Nu * (T - T_{air}) * k_{air} * \pi * dx \dots\dots\dots(V)$$

$$dT/dx = -(T - T_{air}) * Nu * k_{air} * \pi / Q * C_p \dots\dots\dots(VI)$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

in equation (VI), T_{air} is the temperature of surrounding air.

The Nusselt no. (or h) is an essential parameter for calculating filament temperature profile T_x . It can be written

$$N_u * \pi * k_{air} / Q * C_p = 1/L_c$$

Now the equation (VI) can be written as $dT/dx = -(T - T_{air}) * 1/L_c$(VII)

Where, L_c = cooling length

Now integrating the above differential equation (VII),

$$\int dT = -(T - T_{air}) * 1/L_c * \int dx + C$$

or

$$\int \frac{dT}{(T - T_{air})} = -(1/L_c) \int dx + C$$

or

$$\log(T - T_{air}) = -x * 1/L_c + C \dots\dots\dots (VIII)$$

but at $x=0$, $T=T_{melt}$

or

$$\log(T_m - T_{air}) = -0 * 1/L_c + C$$

now putting the value of C in equation (VIII), a relation of temperature at distance x from the spinneret can be find out.

$$\log(T_x - T_{air}) = -x * 1/L_c + \log(T_m - T_{air}) \dots\dots\dots (IX)$$

or

$$\log\left[\frac{(T_x - T_{air})}{(T_m - T_{air})}\right] = -x * 1/L_c$$

or

$$\frac{(T_x - T_{air})}{(T_m - T_{air})} = e^{(-x * 1/L_c)}$$

or

$$(T_x - T_{air}) = (T_m - T_{air}) * e^{(-x * 1/L_c)}$$

or

$$\boxed{T_x = T_{air} + (T_m - T_{air}) * e^{(-x * 1/L_c)}} \dots\dots\dots (X)$$

Where, $L_c = Q * C_p / N_u * \pi * k_{air}$

D. Calculation of filament temperature at different distance

Now calculating filament temperature T_x for denier 126/36 at take up speed 3200 mpm for a distance of 1meter from spinneret.

Q for 126/36 PET yarn
 $= 126 * 3200 / 9000 = 44.8 \text{ gms/ min}$
 $= 44.8 / 36 / 60 * 10^{-3} \text{ Kg/s/hole}$
 $= 0.02 * 10^{-3} \text{ Kg/s/hole}$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

Now, calculating L_c for given throughput for 126/36 denier. $L_c = Q * C_p / N_u * \pi * k_{air}$
Here, nusselt number⁸ = 0.716 for 126/36 denier

$$\begin{aligned} L_c &= 0.02 * 10^{-3} * 1005.7 / 0.756 * 3.14 * 0.026 \\ &= 0.020114 / 30 * 10^{-3} \\ &= 0.323 \text{ meter} \end{aligned}$$

By substituting the values of x , T_{air} , T_{melt} , N_u , k_{air} , Q and C_p in equation (VIII), and get, T_x ($x=1$ meter for 126/36 PET yarn) = $20^{\circ}C + (285-20)^{\circ}C * e^{-1/0.323}$ temperature of quench air and melt temperature of polymer are taken in $^{\circ}C$ instead of in $^{\circ}K$

$$\begin{aligned} &= 20^{\circ}C + (285-20)^{\circ}C * e^{-1/0.323} \\ &= 20^{\circ}C + (285-20)^{\circ}C * e^{-3.0968} \\ &= 20 + 265 * e^{3.0968} \\ &= 20 + 265 / 2.7^{3.0968} \\ &= 20 + 11.975 \\ &= 31.975^{\circ}C \end{aligned}$$

Similarly calculating temperature of yarn at ($x= 1$ meter) for 240/12 PET multifilament
 Q for 240/12

$$\begin{aligned} &= 240 * 3500 / 9000 = 93.33 \text{ gms/ min} \\ &= 93.33 / 12 / 60 * 10^{-3} \text{ Kg/s/hole} \\ &= 0.129 * 10^{-3} \text{ Kg/s/hole} \end{aligned}$$

Now, calculating L_c for single filament of 240/12 PET yarn (denier of single filament is 20) $L_c = Q * C_p / N_u * \pi * k_{air}$

Here, Nusselt number for 240/12 denier = 1.009

$$\begin{aligned} L_c &= 0.129 * 10^{-3} * 1005.7 / 3.14 * 1.008 * 0.026 \\ &= 1.5765 \text{ meter} \end{aligned}$$

By substituting the values of x , T_{air} , T_{melt} , N_u , k_{air} , Q and C_p in equation (X), and get, T_x ($x=1$ meter for 240/12 PET yarn) = $20^{\circ}C + (285-20)^{\circ}C * e^{-1/1.5765}$ temperature of quench air and melt temperature of polymer are taken in $^{\circ}C$ instead of in $^{\circ}K$

$$\begin{aligned} &= 20 + 265 * e^{-1/1.5765} \\ &= 20 + 265 / 2.7^{0.6343} \\ &= 20 + 265 / 1.877 \\ &= 20 + 141.18 \\ &= 161.18^{\circ}C \end{aligned}$$

Similarly $x= 1.5$ meter for 240/12

We substitute the values of x , T_{air} , T_{melt} , N_u , k_{air} , Q and C_p in equation (X), and get, T_x ($x=1.5$ meter for 240/12 PET yarn) = $20^{\circ}C + (285-20)^{\circ}C * e^{-1.5/1.5765}$ temperature of quench air and melt temperature of polymer are taken in $^{\circ}C$ instead of in $^{\circ}K$

$$\begin{aligned} &= 20 + 265 * e^{-(1.5/1.5765)} \\ &= 20 + 265 / 2.7^{0.9515} \\ &= 20 + 265 / 2.5730 \\ &= 20 + 102.99 \\ &= 122.99^{\circ}C \end{aligned}$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

Similarly $x = 2$ meter for 240/12

We substitute the values of x , T_{air} , T_{melt} , N_u , k_{air} , Q and C_p in equation (X), and get, T_x ($x = 2$ meter for 240/12 PET yarn) $= 20^{\circ}C + (285 - 20)^{\circ}C * e^{-2/1.5765}$ temperature of quench air and melt temperature of polymer are taken in $^{\circ}C$ instead of in $^{\circ}K$

$$= 20 + 265 * e^{-(2/1.5765)}$$

$$= 20 + 265 / 2.7^{1.2686}$$

$$= 20 + 265 / 3.5255$$

$$= 20 + 75.166$$

$$= 95.166^{\circ}C$$

Similarly $x = 2.5$ meter for 240/12

We substitute the values of x , T_{air} , T_{melt} , N_u , k_{air} , Q and C_p in equation (X), and get, T_x ($x = 2.5$ meter for 240/12 PET yarn) $= 20^{\circ}C + (285 - 20)^{\circ}C * e^{-2.5/1.5765}$ temperature of quench air and melt temperature of polymer are taken in $^{\circ}C$ instead of in $^{\circ}K$

$$= 20 + 265 * e^{-(2.5/1.5765)}$$

$$= 20 + 265 / 2.7^{1.5858}$$

$$= 20 + 265 / 4.8312$$

$$= 20 + 54.85$$

$$= 74.85^{\circ}C$$

IV. LIMITATIONS AND COCLUSION

Spinning machines supplied by various leading manufacturers give quench air screen size of 1.5 meters. Therefore if spinners want to quench the filaments up to $80^{\circ}C$ (below glass transition temperature of polyester) of 240/12 PET yarn at the distance 1.5 meters from the spinneret then one has to modify the quench air parameters.

To overcome the above limitation it is suggested to keep quench air temperature at $17^{\circ}C$ and to increase the air velocity 1.0 m/s from 0.5 m/s. Now calculating the thread line temperature from equation (X) in the case of mother yarn 240/12 polyester.

Now for $X = 1.5$ m, quench air temperature $17^{\circ}C$, quench air velocity = 1.0 m/s in case of 240/12 polyester yarn.

Re of quench air $17^{\circ}C$ for 240/12 PET yarn = DV/v , (here $D = 45.43 * 10^{-6}$ meter, V (velocity of air) = 1.0 m/s and $v = 15.69 * 10^{-6} m^2/s$)

$$Re = 45.43 * 10^{-6} * 1.0 / 15.69 * 10^{-6} \\ = 2.895$$

And from equation (X) filament temperature T_x at 1.5 m distance from spinneret will be

$$T_{x(x=1.5\text{ m})} = T_{air} + (T_{melt} - T_{air}) * e^{-x/L_c}$$

$N_u = hd/k = CR_c^m P_r^{1/3}$ Where $C = 0.989$ and $m = 0.33$ are constant of this equation for circular cylinder in cross flow

$$N_u \text{ (of quench air at } 17^{\circ}C) = 0.99 * 2.895^{0.33} * 0.70^{0.33} \\ = 0.99 * 1.42 * 0.89$$

N_u (of quench air at $17^{\circ}C$) = 1.2511 of quench air for 240/12 PET yarn

Now, calculating L_c for given throughput for 240/12 denier. $L_c = Q * C_p / N_u * \pi * k_{air}$

Here, Nusselt number for 240/12 denier = 1.2511

$$L_c = 0.129 * 10^{-3} * 1005.7 / 3.14 * 1.2511 * 0.0262 \\ = 1.260 \text{ meter}$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

By substituting the values of x , T_{air} , T_{melt} , N_u , k_{air} , Q and C_p in equation (X), and get, T_x ($x=1.5$ meter for 240/12 PET yarn for 17°C quench air) $=17^\circ\text{C} + (285-17)^\circ\text{C} * e^{-\left(\frac{1.5}{1.260}\right)}$ temperature of quench air and melt temperature of polymer are taken in $^\circ\text{C}$ instead of in $^\circ\text{kelvin}$

$$\begin{aligned} &=17 + (285-17)^\circ\text{C} * e^{-\left(\frac{1.5}{1.260}\right)} \\ &=17+268*e^{-1.190} \\ &=17+(268/e^{(1.19)}) \\ &=17+268/2.7^{1.190} \\ &=17+268/3.26 \\ &=17+82.20 \\ &=99.20^\circ\text{C} \end{aligned}$$

Similarly, T_x ($x=2$ meter for 240/12 PET yarn for 17°C quench air) $=17^\circ\text{C} + (285-17)^\circ\text{C} * e^{-\left(\frac{2}{1.260}\right)}$ temperature of quench air and melt temperature of polymer are taken in $^\circ\text{C}$ instead of in $^\circ\text{kelvin}$

$$\begin{aligned} &=17 + (285-17)^\circ\text{C} * e^{-\left(\frac{2}{1.260}\right)} \\ &=17+(268*e^{-1.587}) \\ &=17+268/e^{1.587} \\ &=17+268/2.7^{1.587} \\ &=17+268/4.837 \\ &=17+55.40 \\ &=72.40^\circ\text{C} \end{aligned}$$

For 1.5m quench chambers spinner can not apply spin finish to filament bundle at the bottom of the quench air screen. Therefore spinner is force to apply spin finish at take up instead at the bottom of quench chamber.

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