International Journal of Engineering Research and Development
e-ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 11, Issue 11 (November 2015), PP.18-26

Estimation of Quench Air Quantity for a Given Throughput in PET Melt Spinning

Dr. S. S. Bhattacharya[1], *D.K. Sullere*[2]
[1]M.S. university, Professor Textile Engg. Dept, Faculty of Engineering & Technology, Vadodara, Gujarat, India
[2]M.S. Polytechnic, M.Text, MBA, Principal, Surat, Gujarat, India

Abstract:- Quenching is one of the most important operation in the melt spinning process of thermoplastic polymers. It helps to develop structural changes in the fibres and thus mechanical properties of the yarn. Quench air parameters are designed depending on the titre plan of the spinners. Main fan size, quench duct design, duct pressure, quench screens sizes and quench air velocity is given by machines suppliers. But all the detailed calculation of quench air quantity are too be carried out at plant level and quench air parameters are to be adjusted as per denier of the single filament .

Keywords:- Quench air, Heat transfer co-efficient, Cooling length, Viscoelastic ,Temperature, Polyester

I. INTRODUCTION

There are mainly three steps involved in melt spinning of polyester:

1. Melting and extrusion of dried polymer chips or present continuous polymerisation system,
2. Quenching of molten polymer below glass transition temperature (T.G.) and then,
3. Winding at take-up

Quenching is supposed to be the heart of melt spinning process. It is the process in which fibre formation takes place. During quenching axial draw force due to higher take-up speed caused orientation of molecular chains and slight induced crystallization also. It is the zone between spinneret and take-up responsible for developing physical properties in the continuous filaments.

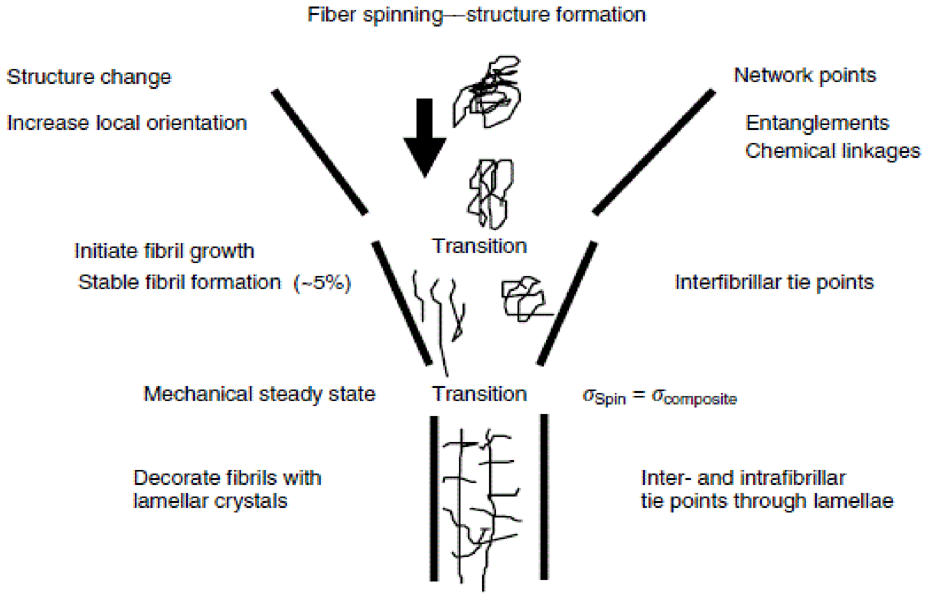


Fig.1: Fibre structure formation

In PET melt spinning quenching has a major role. The physical properties of filaments develop just above glass transition temperature (Tg) of PET polymer in spinning line. Quench air quantity requirement is generally supplied by machinery suppliers eg. M/S Barmag, TMT, DHP and M/S Beijing chon lee based on titre plan given by customers.

Generally only quench screen dimensions, quench duct pressure, air velocity and quench air temperature are given by machine suppliers. Actual quench air calculations are not given by them considering it to be as trade secret.

Air quench chambers are means of cooling and solidifying melt spun filaments bundles coming out from spinneret bores for winding in a few meters distance[1]. 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, tenacity, young's modulus, etc. Which are subjected to high and consistently rising standard requirements.

II. THEORETICAL ASPECTS OF MELT SPINNING AND QUENCHING

A. Rheological Equations of State (2,3,4)

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.

$$\sigma(x) = \mu(x).\frac{d}{dx} v(x) \qquad \text{...................................(I)}$$

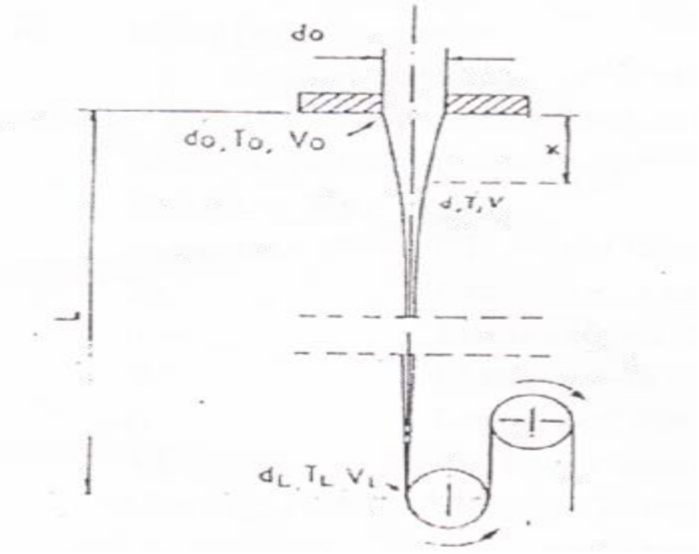


Fig 2: Schematic diagram of PET melt spinning

B. General features of Melt Spinning

Formation[5] 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 tack 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) are, often spun into heat called 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 m/min (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, precipitator agents, 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 spinnerets melts.

Therefore the condition of continuity in a steady state reads -

$$\rho(x)V(x)A(x) = W \text{ Constant } \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(II)$$

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. Principal Process Variables in Melt Spinning

The[6] process can be characterized quantitatively in terms of several process variables. Three groups of such variables can be distinguished:

i. Primary Variables

Pre-determined technical parameters acting as boundary or initial conditions for the dynamic equation (material characteristics, condition of extrusion, take up, etc.)

ii. Secondary Variables

Rated to primary ones by the continuity equation (mentioned above) or similar relation-ships.

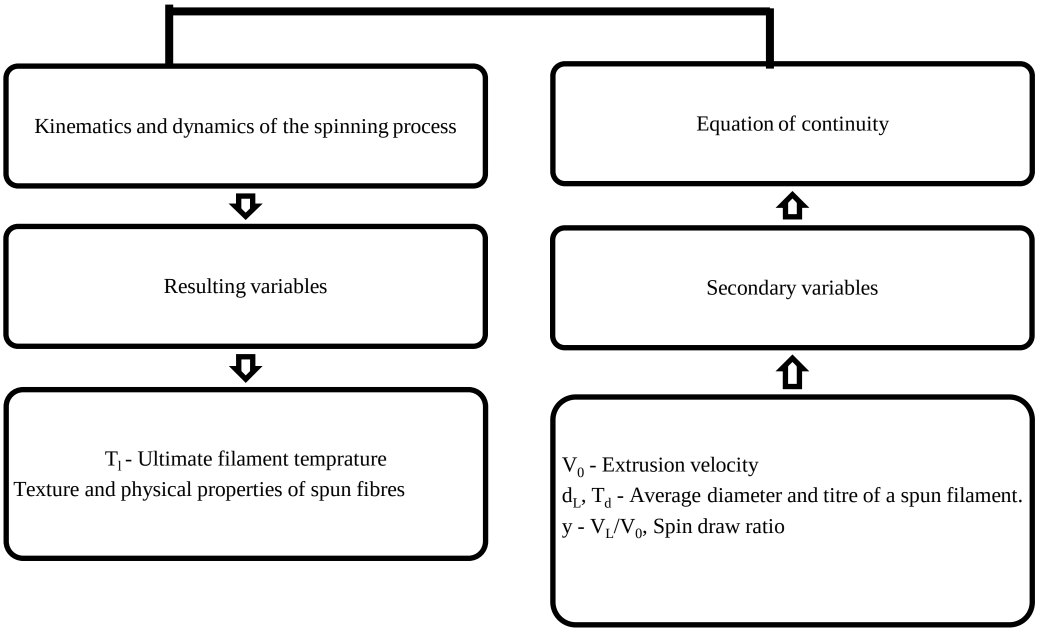
iii. Resulting Variables

e.g. Take up tension or texture of a spun filament determined by primary variables and the kinematics of solidification, phase and structural transformation, etc.

More important process variables are listed as under:

Primary Variables

Material - Chemical composition, molecular structure, physical behaviour
T_0 - Extrusion Temperature
$n., d_0, I_0$ - Dimensions and number of spinneret orifices
W - Mass out-flow
L - Length of the spinning path
V_L – Tack up velocity
Cooling conditions - Temperature, T_W, nature and flow of the cooling medium, heating cell, etc.



D. QUENCHING OF FILAMENTS

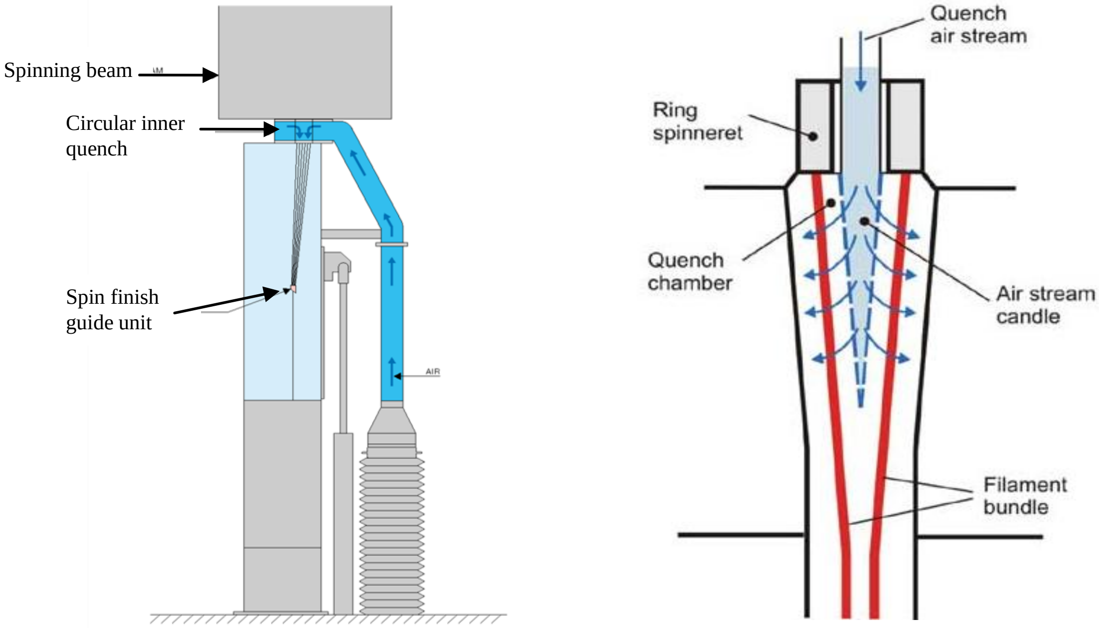
Between the spinneret and the take-up mechanism the yarn path can be divided into three zones:

- ⇨ 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.

D.1 TYPES OF COOLING WITH QUENCH AIR [8]

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)



(3a) **(3b)**

Fig 3: a) CIQ (Circular Inflow Quench) system[9]
b) COQ (Circular outflow quench) system[9]

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 flow utilization of air is up to 70%.

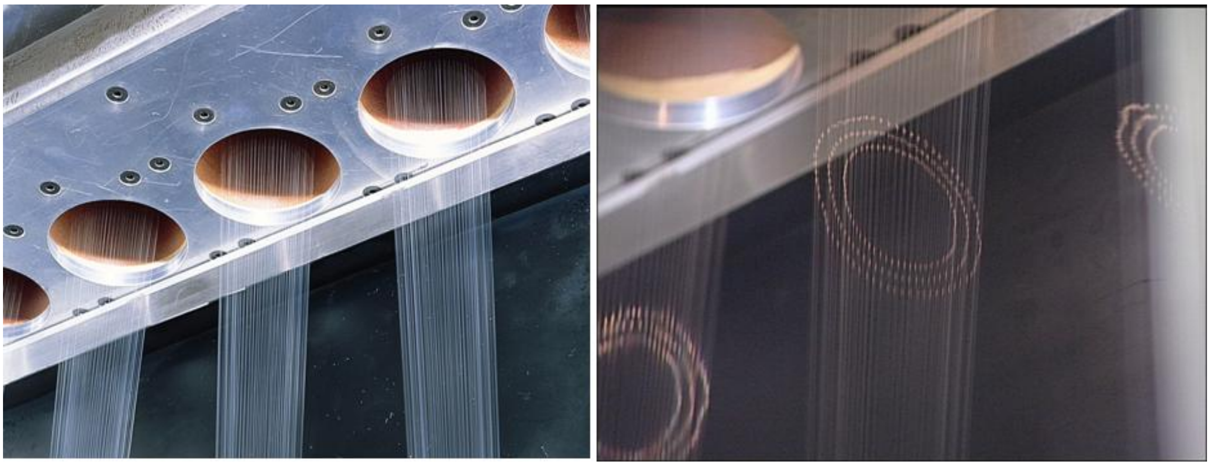
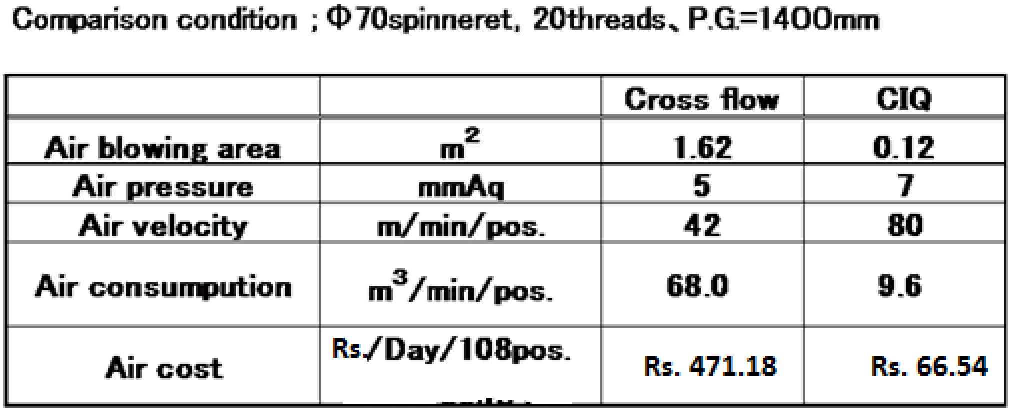


Fig 4: 0.3dpf High-Multi yarn Circular inflow quench air system [9]

By modifying quench air system from cross flow type to circular inflow type. A significant reduction in air quantity is observed and other comparative parameters of quench air are shown in below table l.

Table I: Comparison of air consumption with CIQ & Cross flow [9]



Comparison condition ; Φ70spinneret, 20threads、P.G.=1400mm

		Cross flow	CIQ
Air blowing area	m^2	1.62	0.12
Air pressure	mmAq	5	7
Air velocity	m/min/pos.	42	80
Air consumpution	m^3/min/pos.	68.0	9.6
Air cost	Rs./Day/108pos.	Rs. 471.18	Rs. 66.54

D.2 Calculation of quench air quantities[7]

Here the conditions according to Fig. 5 apply the rheological state equation

$$\sigma(x) = \mu(x).\frac{d}{dx}v(x)$$

and the stability criterion

$$\sigma < \sigma_n \ = \ \mu(x) \ \& \ \frac{d}{dx}v(x) < \frac{d}{dx}v(x)_{\text{critical}}$$

From this follows that a filament can be spun and taken up if it is above the critical titre. This example, especially the catenary[7] curve, is different for every polymer. It is assumed here that σ_n is proportional to the draw viscosity μ.

This filament with almost no cross stiffness forms in a first approximation catenary[7] with the additional conditions resulting from Fig. 5. The degree of deviation as caused by cross flowing quench air, the draw-down tension from the spinneret bore must be less than melt tenacity and the final take-off tension SE = S_0 + R + 0. Here are R filament in the withdrawn air and G = filament weight between spinneret and take-off godets.

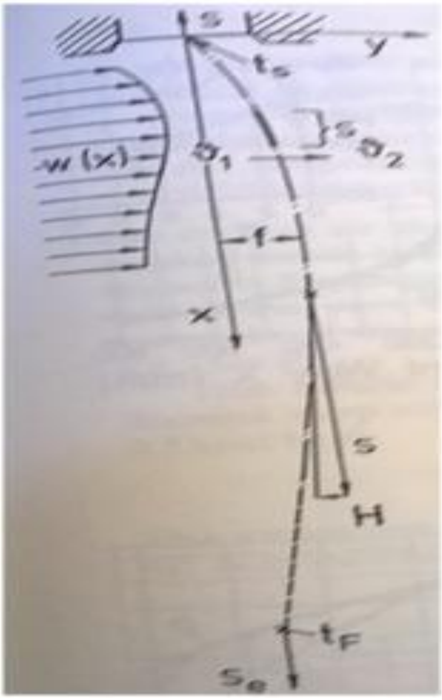


Fig: 5 Force along the thread path for melt spinning with cross flow air quench.

For the thermal equilibrium of the following is valid with the nomenclature

$$G_L . C_{L .} (\theta_2 - \theta_1) = G_s \{c . (T_s - T_F) + S\} \text{.....................................(III)}$$

S = melt heat, that somewhere in the area of the quench air w(x) becomes free. For the heat transfer from the yarn to the quench air flows [III]:

$$\alpha(\Delta x, x) = \rho d c \frac{T(x) - T(x+\Delta x)}{4\Delta x (T_m - \theta_m)} \text{...(IV)}$$

The in part very difficult evaluation of these formulas is only possible in approximation and is explained in Fig. 6 with the help of some measurement.

- With the same starting temperature the filament coming from the larger spinneret hole at the same extrusion rate will cool faster due to the larger surface, At this extrusion rate, there is practically no more difference at about 500 mm below the spinneret.

- The same extrusion quantity and take-up speed result in the same finished filament diameter; the spinneret swell increases with decreasing spinneret bores.
- Spinneret swell is lower with air quench than without.
- The air quenched filament cools down faster than the filament without air quench but without any significant difference up to about 300mm below the spinneret Fig 6 (1 & 3).

- The heat transfer coefficients at 800m/min take-up speed are in the average (in w/rn2K)

Table II

	At 400 mm below the spinneret	**at ≥ 600mm**
Without air quench(b)	40... 50	200
With air quench (a)	90... 100	300

For other take-up speeds approximate heat transfer coefficients can be multiplication with (W/W$_0$)°.

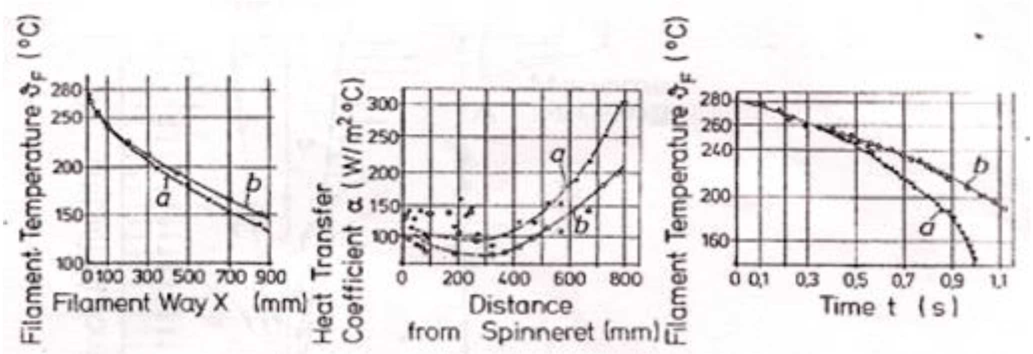


Fig 6: 1. Influence of the cross flowing air cooling on the filament temperature (m=4.5 grams per minute, V_e = 800 rneters per minute, spinneret hole diameter = 0.9 mm)

2. Heat transfer coefficient a between the cooling air & the filament surface as a function of the distance from the spinneret (a - with, b - without air quench)

3. Filament surface temperature as a function of the time after leaving the spinneret hole (data as in 1)

From the mentioned relations the following rough calculation can be deducted:
The necessary cold air quantity for quenching a filament bundle within a narrow space on the sides is

$$Q_L \left[\frac{Nm^3}{h}\right] = \frac{C_F(T_S - T_F) + S}{C_L(\theta - \theta_F)\gamma_L} \qquad \text{.. (V)}$$

Q_L = Air quantity per time unit in Nm^3/h
G_F= Melt or filament quantity per time unit (kg/h)
γ_L= Specific weight (density) of the air = 1.2 kg/rn3 at 20 °C
T = Polymer temperature [°C] with S for melt, F for filament
θ = Air temperature [°C] with 2 at the lower end and 1 at the beginning of the quench chamber
$C_{L =}$ 0.25 kcal/kgK (at 20^0 , 1 bar)

The cooling air should normally have more than 80 % relative humidity. The yarn temperature to be reached needs to be ‘F < TG (glass transition temperature of the spin mass) minus a minor safety distance. Experience and many spinning trials show that filament breakages increase five to ten fold if the yarn is not below the glass transition temperature before the first contact with solid materials. If this is not possible it is necessary to take the increased number of breaks into account, e.g. for PP.

This results in a first rough formula for the necessary air quantity to cool an uninterrupted filament warp with (T_s — T_F) ≈235 ± 15°C, a melt heat S 30 . . . .55 kcal/kg and a specific heat of 0.5 kcal/kg K.
$Q_L\ in\ Nm^3$/h/G_F in Kg/h = 270/$\Delta\theta_{L,Permi\ ssible}$ [^{0}C]

This means that with a permissible increase of the air temperature of 10 K QL/GF becomes 27 Nm^3/kg.

D.3 Quench air flow around and in a spinning multi filament bundle.
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 point made for example by an oiler pin and/or thread guide.
Zone D — Close filament bundle up to the take-up machine.

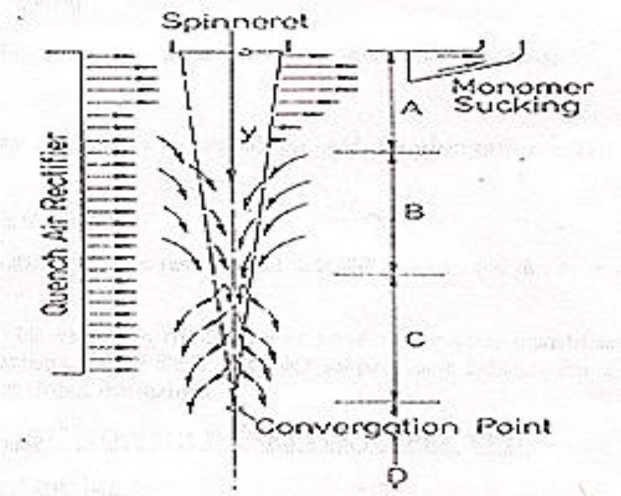


Fig 7: Quench air flow [(7)]

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.

III. CALCULATIONS OF QUENCH AIR QUANTITY (ACTUAL AND THEORETICAL) FOR A GIVEN THROUGHPUT

A. Calculation of quench air requirement per position for filament yarn:

Generally used terms

➔1 denier is defined as 9000 meters of a single filament weighs 1 g. For example 210 denier means 9000 m of yarn weighs 210 g.
➔ 1 dtex id defined as 10000 meters of a single filament weighs 1 g. For example 210 dtex means 10000 m of yarn weighs 210 g.
➔ From 1 & 2, we have the relation 1 dtex = 1.111 denier.
➔ Screen size in mm --1200*1170 (effective 1050*995)
➔ Spinneret size mm OD*ID*thickness=77*72*20 .
➔ Air velocity – 0.5 meter/sec.
➔ Effective width for cooling – Effective Spinneret diameter*nos of end.
➔ Air requirement per pos. = (1.05*0.955*0.5*3600)
=1880.55 m^3/ Hrs
➔ 3 nos. fan are running @ 70 of capacity each having 120000 CFM (Cubic feet per meter)
Per spinning pos. air consumption cubic meter/hr =(0.7*3*120000*1.7/240)
Per spinning pos. air consumption cubic meter/hr = 1785

B. Calculating filament yarn throughput per position:

1. Spinning denier (d) = 126 den
2. Spinning Speed (N) = 3100 meters per minute
3. No. of ends per position (z) = 10
4. Nos. of filament per end = 36
5. Filament yarn throughput (W) , kg/hr = (0.06*d*N*z)/9000
   W kg/hr = 26.04

C. Heat load q ON QUENCH SYSTEM PER POSITION (FILAMENT YARN) :

Melt temp. of PET (T-melt) = 285 degree Celsius
Freezing temp. of PET (T-freeze) = 260 degree Celsius
Avg. Sp heat @ melt temp.(Cp-melt)= 0.48 kcal/kg /degree Celsius
Latent heat of fusion of PET (λ) = 11.5 kcal/kg /degree Celsius
Filaments cooled to temp (T-final) = 60 degree Celsius
Avg. Sp heat @ Solid fiber (Cp-solid)=0.40 kcal/kg /degree Celsius
q=(W*cp-melt*(T-melt-T-freeze))+(W* λ)+(W*Cp-solid*(T-freeze - T-final))
Q kcal/hr =2689

D. Minimum theoretical amount of quench air per position (filament yarn):

1. Quench air supply temperature = 20 degree Celsius
2. Quench air exit temperature = 40 degree Celsius
3. Quench air pressure = 0.007kg/(cm^2)g (Assuming 70mmwc or 700 Pascal)
4. Sp heat of quench air = 0.25 kcal/kg degree Celsius
5. Mass flow of QA required = 537.82 kg/hr ,2689=mass of qa*(40-20)*cp of air(0.25kcal/kg 0c
6. Density of QA = 1.25 kg/m^3
7. Actual volume Flow = 430.26 m^3/hr
8. Volume flow at NTP (Q-theoretical) = 403.62 Nm^3/hr

E. Actual amount of quench air required per position (Filament yarn):

These calculations applicable for filament yarn only where cross flow QA system is followed. Table for row number factor for the quench air quantity
Actual amount of QA required = 4*Min. Theoretical Amount of air factor from table
Example: The term 4 has been taken as in cross flow only 25% air is used actual cooling
For f= 4, Q-act= Q-theoretical*1.113*4 =403.62*1.113*4
=1796.9Nm^3/hr

Table III

Polymer	T-melt , Degree Celsius	T-quench supply degree Celsius	T-quench exit degree Celsius	F factor for no of filament rows per spinneret		
				4	7	9
PET	285	20	40	1.113	1.188	1.735

F. Exit temperature of qa based on actual quench air flow (Filament yarn):

1. Actual QA Vol. flow at NTP (Q-act) = 1796.9 Nm^3/hr
2. Density of QA at NTP = 1.31 kg/m^3
3. Actual mass flow of QA = 2353.96 kg/hr
4. Sp heat of quench air = 0.25 kcal/kg /degree Celsius
5. Quench Air supply temperature = 20 degree Celsius
6. Heat load for quench air = 2689 kcal/hr
7. Exit Temperature = 24.57degree Celsius
8. Mass of QA*diff. of temp*cp of air=q(heat load)
9. Diff of exit and inlet temp.=2689/2353.96*0.25=4.57 degree Celsius

V. CONCLUSION

In this paper calculations are made of the quantity of quench air depending on melt throughput and accordingly air requirement to dissipate the melt heat and further bringing the temperature of filaments below glass transition temperature of polymer ,so that smooth winding could be possible at take-up. But if denier per filament is higher by 4-6 times in the same spinning line then spinner have to think in terms of increasing length of quench screen, reducing quench air inlet temperature and increasing velocity of quench air and for that modifications in quench air system is required to have same quenching effect even if our throughput remains the same.

From 120/36 a PET multifilament yarn running at 3100 meters per minute take- up speed quench air flow calculated:
i. For given throughput,
ii. As per screen size and
iii. As per actual plant fan size data are as under.

Table V

Product : POY							
Denier	Spinning Speed , m/min	Polymer through put , kg/hr	QA supply temp, degree Celsius	QA return tem degree Celsius	No. of rows per spinneret (1 Position)	Row factor	QA flow Nm^3/hr
126	3100	26.04	20	24.6	4	1.113	1796.9
	As per screen size air consumption						1880.55
	plant data as fan size						1785

REFERENCES

[1]. Made—made fibres year book 1987,published by Chem.Text,F. Fourne Alfter,p.64
[2]. J. A. Brydson. , Properties of polymer melts, Butterworth & Co. (Publishers) Ltd. England.
[3]. Green, H., industrial Rehology & Rheological Structures, Wiley, New York (1949).
[4]. Ferray, J.D. , Viscoelastic properties of polymer, Wiley, New York (1961).
[5]. Fundamentals of melt spinning by Ziabicki,1976.
[6]. D.W. Ihn & J.A. Cuculo, J. Macrombd, Sci. Rev. Macromol. Chem. Phys. C 24 (3), 419 – 496 (1984).
[7]. F. Fourne, Synthetic Fibre , Carl hanser Verlarg, Munich (1999).
[8]. Hutt : Des Ingenieurs Taschenbuch : Ern& Sihn : Berlin, 1955, 28th edition, p. 663.
[9]. TMT machinery Inc.