Fundamentals of Gas Management As Applied To Nonwovens Production

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Abstract

Nonwovens production is often adversely affected by non-uniformity associated with fiber laydown and web formation. This non-uniformity is in part a result of the complex interactions between the air streams and the spinning process. Currently, the amount of available research in this area has been minimal with few engineering solutions or references to guide equipment designers. The purpose of this paper is to explore and explain the interaction of air streams engaged in the laying down of nonwovens product onto a porous conveyor or laydown belt. This paper concentrates on the space above the laydown table and the interaction of the fiber stream with the surrounding environment. In this paper, the influence of the ambient and conditioned air will be examined from the spinneret to the forming table. It is assumed for the purposes of this paper that the laydown vacuum is sufficient to evacuate 100% of the combined air streams and a cross-flow quench is used.

Why is air management above the forming or laydown table so important? The control of the air that is feeding the system affects the entire forming area and has a direct impact on web formation and energy cost. The size and complexity of air removal systems are also directly affected by the quantity of entrained air expected in the laydown process. By understanding the process and applying better management techniques, the design, equipment and operational cost for the laydown area can be reduced and also ensure acceptable web formation.

Does entrainment of ambient air affect the formation of the nonwovens web? The formation of the web is directly affected by the amount and aspect of the entrained air available to the system. The interaction between the air laid stream and the surrounding air can cause disruptive eddies within the laydown profile of the nonwoven fiber.

Can the entrained air streams be controlled effectively? By actively supplying the entrained air along the thread path of the fibers and using control devices, such as dampers or valves, adequate control of the entrained air can be attained.

Fiber Laydown Path and Configuration

The basic process in the formation of a non-woven starts at the spinneret where filaments are extruded, then quenched, charged and drawn (mechanical, air jet, or in combination), diffused, and then discharged to the forming belt of the forming table where vacuum is applied to hold the filaments on the belt. An individual filament moving within the fluid stream (air) will entrain a quantity of the fluid stream depending on the surface friction of the filament and the coefficient of friction of the fluid stream.

The fiber may have a discharge velocity range from the spinneret of 1 to 1.5 meters per second (m/s) or 196 to 295 feet per minute (fpm) for most polymers (PA, PET, PP, PE) (Ref. 1) Within approximately 2 inches (50.8 mm) from the spinneret or die, a cross flow air stream from the quench is introduced with a velocity in the range of 0.4 to 0.9 m/s or 79 to 177 fpm face velocity. If it is air drawn, the fiber will pass through a venturi type jet which provides the drawing force on the fiber. Air is also entrained and the composite stream accelerates to a much higher velocity than the fiber jet velocity at the spinneret (up to 6000 m/min or 19685 fpm). If mechanical draw is used, then the unit accelerates the fiber by the roll speed (rpm) which also entrains air with the fiber stream. A diffuser is used to spread the fibers to form a mat on the laydown belt. This entrained air is often unpredictable and can require many hours to modify and tune until the process can successfully be used to produce a uniform nonwovens web. The structures above a laydown table represent a complicated geometry for the air streams involved. Enclosures or guides influence the air mass entrained and final velocity at discharge of the unit. Many different configurations exist within

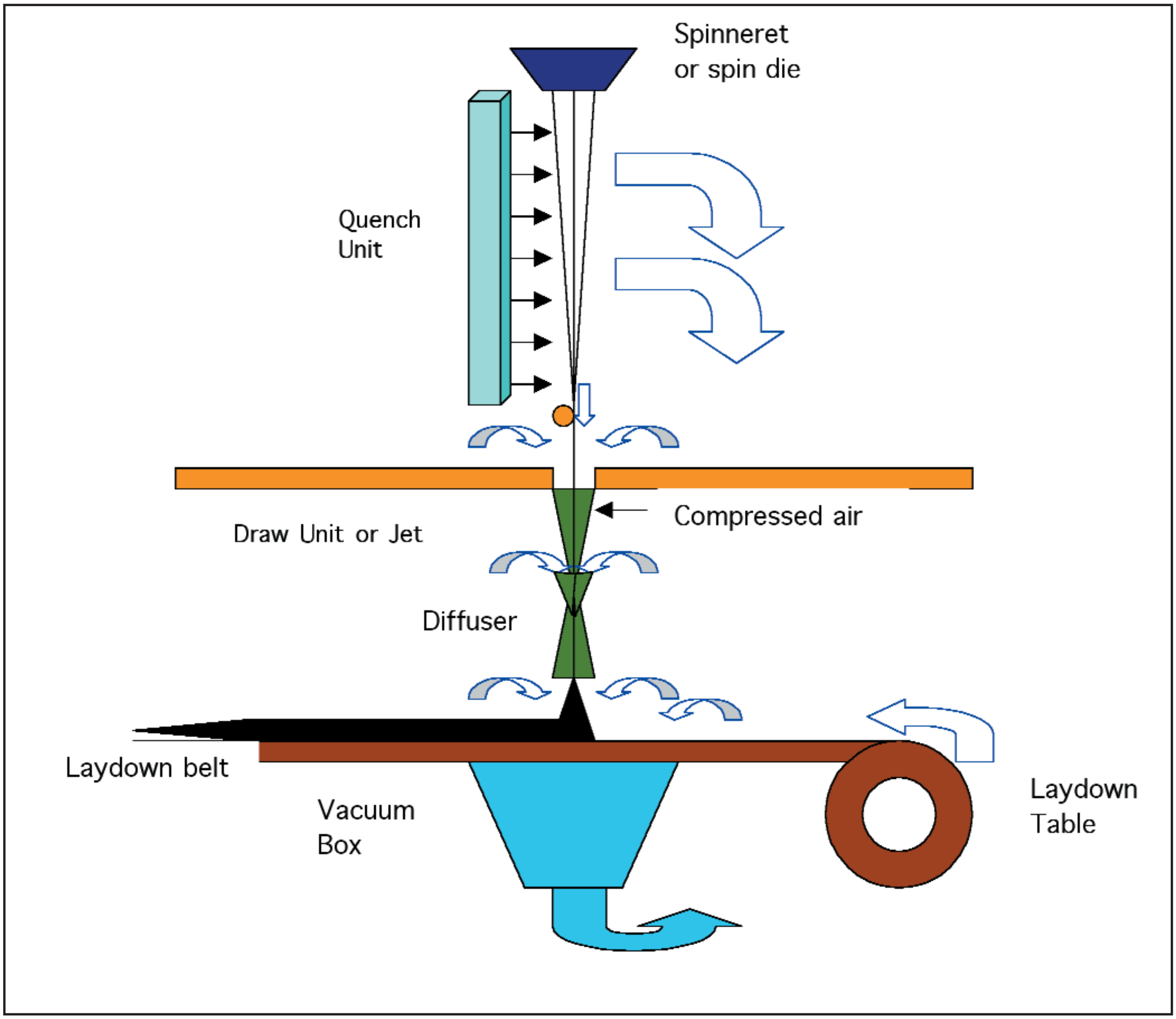

Figure 1
AIR DRAWN NONWOVENS FIBER PATH

the spectrum of synthetic fiber production, but all nonwovens production has the same general characteristics.

Describing the Process

A singular fiber being extruded from a die can be described in terms of a circular jet within the laminar range. The following is valid for each vertical position (x) of the thread path, $\gamma * F(x) * v(x) = G$ where γ = melt density, F is the filament cross-section, v is the velocity, and G is the mass throughput per bore. For a round filament $F = (\pi * d^2)/4$ therefore the filament diameter is $\mathbf{d(x) = 2[G/[\pi * \gamma * v(x)]]^{0.5}}$ The extrusion velocity can be calculated as $\mathbf{v_B = 4 * G_B / \pi * d_{hole} 2 * \gamma_{melt}}$ where G_B is the filament mass per hole and d_{hole} is the diameter of the capillary. [1] As the fiber passes through the quench zone, air is entrained and a symmetrical boundary is formed around each fiber. This stream can be thought of as the initial motive force for the combined air pump that is formed by all the associated components. The fiber velocity used in calculating the momentum transfer between the air and fiber is the take-up speed or draw speed. If the fiber was passing through an air space of relatively still air ($m_{air}\ v_{air} \rightarrow 0$), i.e. where the momentum of the air mass is approximately zero, an induced air stream will be produced by the friction of the filament's surface.

The introduction of the quench air perpendicular to the fiber path induces additional shear stress to the fiber. The fiber pulls or entrains the air based upon the amount of drag generated by the surface friction of the fiber. The speed at which the fiber is traveling and the drag or frictional coefficient determines how much of a pumping action is generated into the near field of the fiber. The shear stress τ_s describes the momentum transfer between the surrounding air to the filament. A dimensionless air friction coefficient is required to calculate the amount of stress induced upon the fiber by the quench air. The air resistance or turbulence can be expressed in terms of the Reynolds number for the quench air. For the purposes of this paper, the shear stress for all of filaments is approximately the same.

The Reynolds number for the unquenched filament can be calculated using the following formula. $Re = (\rho_{air} * v_f * 2\ r_f) / \eta_{air}$. [4] The Reynolds number for the quench air can be calculated using the following formula. $Re_{air} = (\rho_{air} * v_{air} * 2\ r_f)\ / \eta_{air}$. The dimensionless air friction coefficient for the quench air for an individual filament can be calculated using the following formula. $c_f = (a_2 / Re)\ (Re^2 + b_2 * Re_{air}^2)^{c2}$. The shear stress can now be calculated using the following formula. $\tau_s = c_f *(\rho_{air}/2) * v_f^2$. Where $\boldsymbol{\rho_{air}}$ is the density of the quench air; $\mathbf{r_f}$ is the radius of the filament; $\mathbf{v_f}$ is the take-up velocity of the filament; $\boldsymbol{\eta_{air}}$ is the dynamic viscosity of the quench air; $\mathbf{Re_{air}}$ is the Reynolds number of the quench air; **Re** is the Reynolds number for the filament; $\mathbf{v_{air}}$ is the face velocity of the quench air; $\mathbf{c_f}$ is the dimensionless air friction coefficient; $\mathbf{a_2}$ is the dimensionless constant of 0.37; $\mathbf{b_2}$ is the dimensionless constant of 4096; $\mathbf{c_2}$ is the dimensionless constant of 0.2. It is important to note that the diameter of the filament is changing as it progresses along the stream path, for general design, use the average diameter if the filament's diameter at different positions along the path is unknown.

The physical properties of the air are changed as quench air heats up as it passes through the fiber bundle and impacts the area. The density of the bundle and type of polymer will determine how much the quench air will increase in temperature. The entrained air is stripped from the combined stream as the bundle is being collapsed. The entrained air from the quench zone is a combination of quench air and room air. The quench air volume must be accounted for in the overall building or work space environment. For example, a quench cabinet that is 48 inches in width and 54 inches in height with a face velocity of 140 fpm has a flow of 2520 ft^3/min. The air entrained by the fibers can be approximated by multiplying the number of fibers $\mathbf{n_f}$ by the quantity of air entrained by an individual fiber. It is important to note that different quench types and configurations will vary the amount of air forced along with the fiber stream.

$$\mathbf{M_{ent} \approx (2\pi * r_f^2 * \rho_f * v_f * n_f * c_f) / \rho_{air}}$$

Where $\mathbf{M_{ent}}$ is the entrained air mass flow rate; $\mathbf{r_f}$ is the radius of the filament; $\mathbf{v_f}$ is the take-up velocity of the filament; $\boldsymbol{\rho_f}$ is the density of the filament; $\mathbf{n_f}$ is the number of filaments; $\boldsymbol{\rho_{air}}$ is the density of the quench air; $\mathbf{c_f}$ is the dimensionless air friction coefficient. For example, 10000 PET fibers with a radius of 0.0762 mm, density of 1.34 gm/cm3, $\mathbf{c_f}$ is 0.008, and take-up velocity of 4000 m/min passing through standard air will yield a flow of approximately 460 SCFM.

The Draw Jet and Diffuser

As the fiber enters the draw jet entrance *(Figure 2)*, the stream is exposed to an air jet nozzle which accelerates the stream drawing the fiber along with the stream. The stress or torque that is presented to the fiber can be described in the same manner as the fiber passing through the quench zone. One difference is that the jet nozzle within the draw jet assembly entrains the fibers along with the air. The entrainment of the combined stream is limited by the power of the jet nozzle and the open area of the draw jet entry. As the jet pressure, ***Ps*** increases, the discharge is limited by the choke velocity of the jet. The impact velocity of the jet v_N on the fiber must be greater than the desired take-up velocity due to the loss of energy equivalent to the torque or stress applied to elongate or draw the fiber. The momentum of the fibers $(F_f = m_f * v_f)$ must also be accounted for in the entrainment of the jet. The momentum through the draw jet can be described by $m_{jet}\ v_{jet} = m_f\ v_f + m_{ent}\ v_{ent} + loss_{friction}$. The velocity of the entrained air and the fiber velocity at the entrance of the jet approach the take-up velocity. The discharge air quantity of the draw jet can be described as $\mathbf{Q_{draw\ jet} = Q_{jet} + Q_{ent} - Q_{fiber}}$.

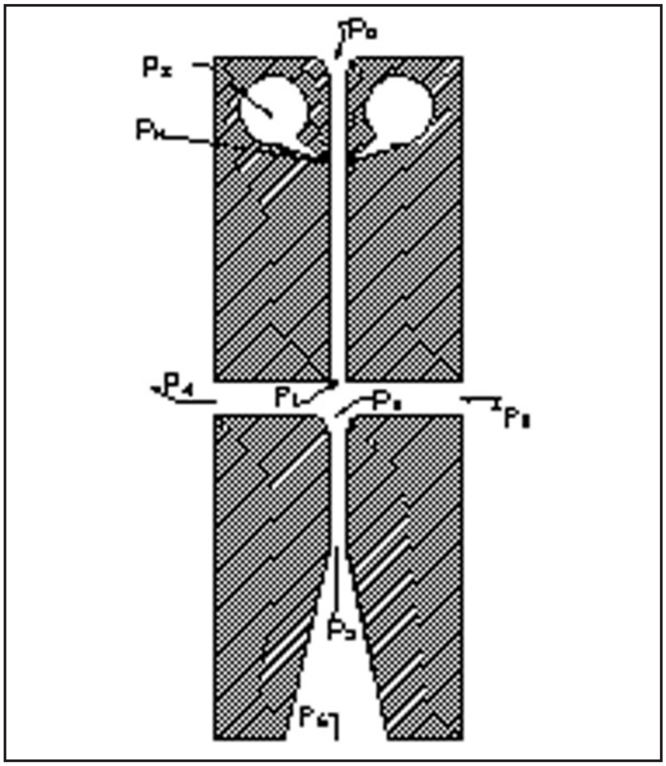

Figure 2
DRAW JET AND DIFFUSER

P_0 is the entrance pressure of the draw jet assembly.
P_N is the nozzle discharge pressure of the draw jet assembly.
P_S is the supply pressure of the draw jet assembly.
P_1 is the discharge pressure of the draw jet assembly.
P_2 is the entrance pressure of the diffuser assembly.
P_3 is the port pressure of the diffuser assembly.
P_4 is the port pressure of the diffuser assembly.
P_5 is the throat pressure of the diffuser assembly.
P_6 is the exit pressure of the diffuser assembly.

The physical properties of the flow stream associated with the different pressures $\mathbf{P_N}$, $\mathbf{P_S}$, $\mathbf{P_0}$ thru $\mathbf{P_6}$ concern the changes in the area, velocity, volume, and density of the flow streams. The entrainment areas correspond to $\mathbf{P_0}$, $\mathbf{P_3}$, and $\mathbf{P_4}$. For example, a draw jet with 0.5 inch gap and 50 inches wide set at 4000 m/min (13123.36 fpm) take-up velocity will have an approximate volumetric flow of 2278 ft^3/min.

As the fiber stream exits the draw mechanism (mechanical, air jet or combined) air is entrained by the forced air stream and fibers and provides the motive force for the diffuser. The motive stream mass flow is the same a $Q_{draw\ jet}$, therefore the amount of entrainment at P3 and P4 is limited by the centerline velocity of the motive stream and the area of the diffuser throat. For example, if the velocity of the draw jet discharge is 3000 fpm and the area of the diffuser throat is 0.2604 ft^2 then the maximum air flow Q_{total} will be 781.2 ft^3/min. $\mathbf{Q_{total} = Q_{draw\ jet} + Q_{P3} + Q_{P4}}$ where the flow rates at P3 and P4 are entrained. If the configuration of the diffuser is symmetrical then $Q_{P3} = Q_{P4}$. The total mass flow rate G_{total} at P5 is $\mathbf{G_{total} = G_{draw\ jet} + G_{air\ @\ P3} + G_{air\ @\ P4} + G_{fiber}}$. As the combined fiber stream passes the diffuser throat, the area increases which slows the stream as the pressure lowers resulting in a wider spray pattern. Although not addressed specifically in this paper, it is important to note that the fibers generally possess some static electrical charge. At this point, as the planes of the diffuser diverge, the fibers are dragged along as the general spray pattern is determined by the distance between the forming belt and the discharge of the diffuser.

Air Entrainment and Free Jets with fibers

Air entrainment is the result of the interaction of the combined momentum of streams and the shredding of the shear or boundary layer as the combined fiber stream passes through the fluid media (air).

The region of flow development for a free jet (any gas) is approximately 6 to 7 nozzle diameters beyond the discharge, the region of flow development for the combined stream of fiber and air is greater than that for a free jet of gas. (Ref. 3) In the case of a slot jet, typically the equivalent hydraulic diameter would be used to determine how far the potential core is extending past the nozzle. The effective distance where the centerline velocity is maintained is based upon the initial velocity and the Reynolds number of the flow stream. In the case of an air drawn nonwoven, the draw jet discharges typically into a diffusion device which extends the effective length as well as changes the profile of the jet discharge. The potential core of the discharge jet is extended further in the vertical axis by the additional mass of the fibers as compared with a free jet of air. In the case of an extruded fiber, the centerline velocity of the fiber is controlled in combination by the jet velocity and the velocity of the take-up or draw units depending on the process. Since the exit velocity is limited by the maximum shear stress of the filament, it is the draw or take-up velocity which has the major effect on entrainment. Additionally, as air/fiber disperses the flow stream's level of instability increases and the same is true for the entrained streams. By recalculating the Reynolds number for air in the area in proximity to the diffuser's discharge, an indication of the instability can be surmised.

Aerodynamic Drag and Filaments

The calculation of the force implied to the air field in terms of the drag generated by the fiber using the general form

$$\mathbf{F_D = {}^1/_2 C_D \rho u^2 A}$$

Where $\mathbf{C_D}$ is the drag coefficient of air, $\boldsymbol{\rho}$ is the density of the air or fiber in this case, **u** is the velocity of the fiber with respect to the air and **A** is the cross-sectional area of the fiber. The general form for aerodynamic drag is shown below, where $\mathbf{A_{frontal}}$ is the face area presented to the air stream.

$$\textbf{Aerodynamic drag} = {}^1/_2 \rho_{air} * A_{frontal} * u^2$$

For example, a fiber passing through a quiescent air space with ambient air would have a drag force of

$$\mathbf{F_D = {}^1/_2 C_D \rho u^2 A = .5*.82*.075*x2.5^2*8.72E^{-8} = 6.675875E^{-8}\ ft*lbs/sec^2\ or\ 9.23E^{-9}N/sec^2}$$

Where $\mathbf{C_D}$ is set at a value of 0.82 (dimensionless); $\boldsymbol{\rho}$ is set at a value of 0.075 lbs/ft^3; **u** is fiber velocity along its length or 2.5 fps at the top; **A** is the cross-sectional area of the fiber or 1.26×10^{-5} in^2 or 8.72×10^{-8} ft^2.

The drag coefficient $\mathbf{C_D}$ is dependant upon the geometric shape and orientation to the flow stream, in the case of the filaments, it would correspond to a small diameter cylinder of infinite length. Structural components above the forming table have corresponding drag coefficients listed in *Table 1.* [8]

Air Management

The management of the air streams influencing the draw jet can be accomplished by actively supplying the entrained air for the systems at the entry points. By effectively enclosing

Table 1

Type	**Drag Coefficient**	**Type**	**Drag Coefficient**
Flat plate	1.28	Cone	0.50
Prism	1.14	Cube	1.05
Sphere	0.07 to 0.50	Angled Cube	0.80
Half sphere	0.42	Long cylinder	0.82
Air foil	0.045	Short cylinder	1.15
Streamlined body	0.045	Streamlined half body	0.09

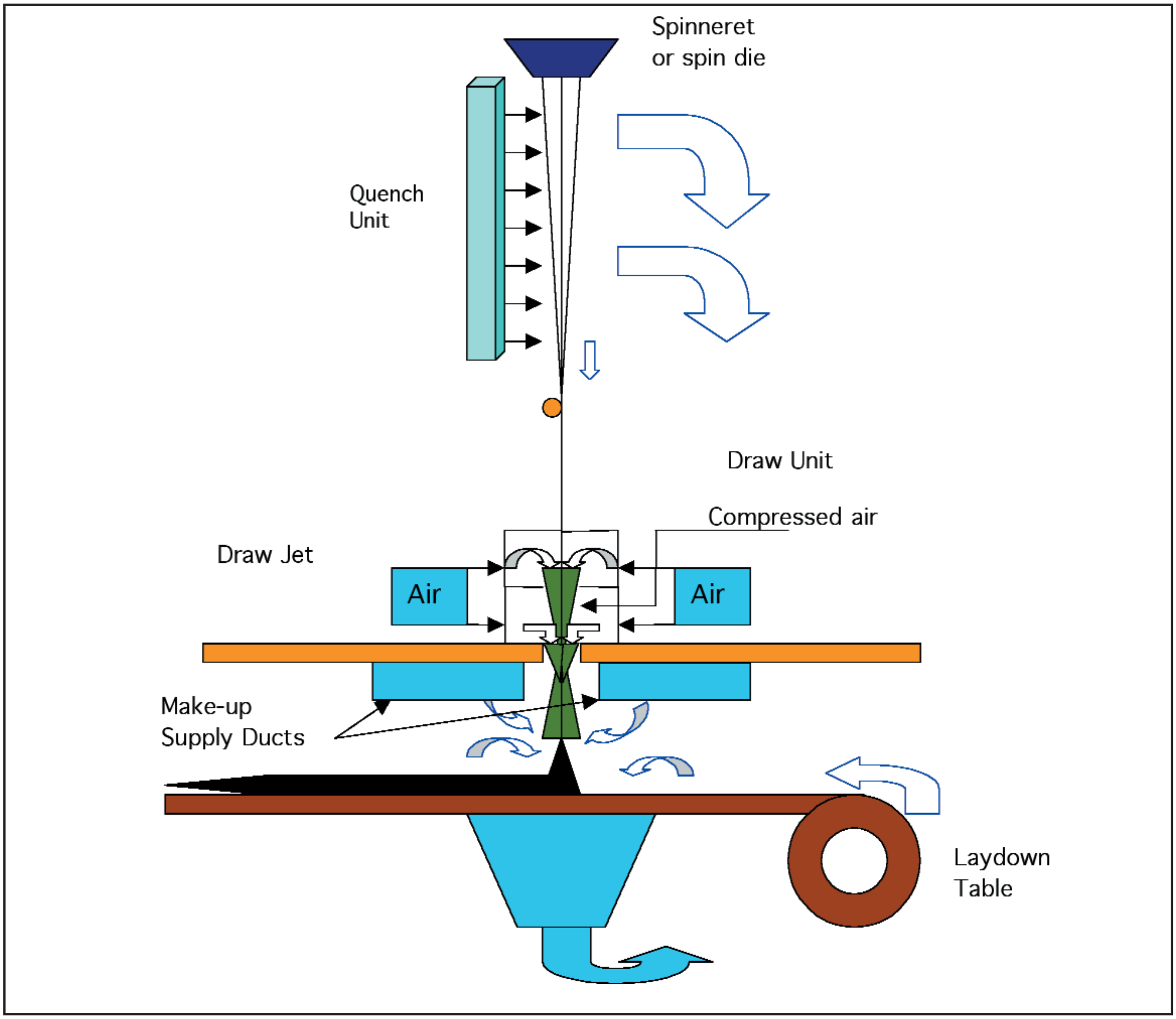

Figure 3
NONWOVENS FIBER PATH WITH MAKE-UP SUPPLY DUCTS FOR LAYDOWN

the draw jet and controlling the entrained air at the inlet, the discharge of the jet is also affected. As the fibers and entrained air are drawn into the draw jet, the distance between the entry and the motive jet determines how effective controlling the entrained flow will be on the stability of the combined stream. The reason for this is that as the combined stream interacts with the jet stream, the turbulence increases in that area as the Reynolds numbers of the flows are $Re_{entry} < Re_{combined} < Re_{jet}$. The jet stream provides a break or isolation zone for the flow stream so as the distance from the entry to the jet stream increases, the more the inlet stream will normalize and the effective isolation will increase. By actively controlling the entrainment, the mass flow through the affected area is changed as the combined stream is pulled through the draw jet.

Another aspect is controlling physical properties of the boundary layer at each end of the draw jet. This is true for a rectilinear draw jet where the length of the slot is much greater than the width of the slot. As the boundary layer forms at the ends, the effective depth of the boundary layer can be managed by allowing the air which comprises the layer to be bled off in a controlled manner. The same is true for the entry of the diffuser even though the centerline velocity of the flow stream decreases as it flows through the diffuser. The use of computational fluid dynamic (CFD) or engineering fluid dynamic (EFD) packages can be used to model the gas flow through the draw jet and diffuser assemblies. By using these aids, a better understanding of how the streams will act can be achieved as the systems are being designed.

The entrained air at the discharge of the diffuser can not be managed in the same manner as the draw jet and diffuser. Even though the discharge flow pattern can be managed in part by controlling the entrained streams at the entrance of the diffuser, other factors such as the forming belt speed and its entrainment, the vacuum distribution under the belt, etc. will have greater impact on the amount of air entrained. The control of the entrained air at the entry of the diffuser can affect the instability of the discharged stream along the length. By choking the entrained flow at the inlet, the areas of instability along the length of the diffuser can be mitigated as the local mass flow is changed.

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