

Properties of Glass Fiber for Filtration: Influence of Forming Process

By Jon F. Bauer, Johns Manville Technical Center, Littleton, Colorado

Abstract

Glass fiber used in filtration applications is typically produced by either of three types of processes: (1) continuous draw, (2) centrifugal (rotary) spinning, or (3) flame attenuation. Each process imparts to the fiber a unique set of characteristics such as diameter, length, and surface chemistry and structure. These in turn dictate the key performance properties of the fiber in nonwoven products. Diameter distribution is perhaps the most fundamental to filtration efficiency; this can vary appreciably with fiberization process even for fibers of the same bulk chemistry and “mean” diameter. Likewise length distributions are unique to each process and, for discontinuous fiber, have a distinct correlation to the diameter distributions. Complete characterization, therefore, often requires bivariate analyses. Finally, glass surface chemistry and structure, which are critically important for key properties such as fiber tensile strength, chemical durability / reactivity, and dispersability, are also highly dependent upon the fiber forming process. By controlling initial glass chemistry and fiberization process parameters, a wide range of fiber dimension, morphologies and surface properties can be achieved. As such glass fiber has some unique opportunities in meeting existing and new demands in filtration markets.

Keywords

Glass Fiber, Filtration, Fiber Diameter, Fiber Length, Fiber Forming Process, Fiber Surface

Introduction

Glass fibers used in nonwoven filtration applications can differ significantly in their physical and chemical properties. These properties in turn affect or even control the performance characteristics of the media in which they are used. It is useful to understand how these fiber properties vary among fiber types and where interdependencies between

individual properties occur.

The most important fiber properties in this regard are diameter, length, and chemical composition. For diameter and length it is really the distribution of these values that is the most relevant measure. Diameter distribution contributes appreciably to media performance properties, most notably filtration efficiency and pressure drop. Likewise fiber length distribution primarily affects physical properties such as tensile and tear strength but can also influence media thickness and thereby efficiencies and “delta P” values as above. Both diameter and length, of course, also impact important media forming properties such as fiber dispersion in whitewaters or other aqueous media.

Fiber chemistry is most frequently thought of in regard to chemical durability; glass types comprising the fibers can vary widely in their resistance to pH, atmospheric moisture, or chemical corrosives. While bulk chemical composition is usually provided or reported for each fiber type, chemical resistance is best measured by the fibers’ specific surface chemistry. Surface chemistry is a function not just of bulk glass composition, but of the specifics of the fiber forming process as well. Some of these dependencies have been reviewed and presented previously [1].

The principle fiber forming processes for manufacturing glass fiber used in filtration applications are (1) continuous draw, (2) rotary spinning, and (3) flame attenuation. Detailed descriptions of each of these processes are available in the literature [2, 3]. Glasses used in each of these processes are optimized with respect to raw material cost, fiber formability, and end product requirements. Their most important forming properties are viscosity and surface tension and the respective temperature variations of each. Beyond glass composition itself, the surrounding environment or atmosphere is also important as it can interact with the newly-forming fiber surface to modify not only the fluid properties, but also the

end properties of the cooled glass fiber. In this manner, key product attributes such as tensile strength and chemical durability can be impacted as well. Surface properties of fibers are also dependent upon cooling rate of the fiber during formation, and thereby dependent upon the diameter. So fiber geometry and fiber chemistry can be well interconnected.

This paper explores the role of fiberization process in determining diameter and length distributions of glass fiber and also how glass chemistry, both bulk and surface come into play to establish the overall dimensions and end properties of the fiber. The fiber manufacturer can use such interdependencies to control the performance characteristics of fibers produced.

FIBER DIMENSION

Continuous Draw (CD) Fiberization

This method of manufacture is perhaps the simplest (and oldest), involving only a single attenuation from a conditioned melt pool. Melt is typically pulled through a myriad of holes in a noble metal (non-reactive) bushing and “stretched” to the desired diameter. As hole sizes and drawing tensions are carefully controlled, the distribution of individual fiber diameters is very narrow. Temperature variations across the bushing are the usual source of dispersity, producing small variations in melt viscosity from hole to hole. The end product is usually a multi-filament continuous strand comprised of several thousand uniformly oriented (parallel) individual fibers.

A typical diameter distribution for a commercial CD fiber is shown in *Figure 1*. The rather uniform drawing environment also leads to diameters which are normally distributed (note the coincidence of arithmetic, geometric, and surface area equivalent means, in *Figure 1*). As such, tensile properties of these fibers are typically quite consistent. Once formed, fibers cool rapidly, so that maximum compressive stresses are generated at the fiber surfaces, augmenting the fibers’ intrinsic tensile strength. Commercial CD fibers are produced with mean diameters ranging from about 3 μm to 25 μm , but those with mean diameters of 8 to 16 μm are most common. Fibers finer than about 6 μm become quite difficult to pull, at least economically, and so at this point production typically shifts to secondary attenuation processes as discussed below.

Fiber length, of course, is controlled by cutting or chopping either during or after production, and is therefore, independent of the forming process itself.

Rotary Spinning (RS)

Rotary spinning is generally employed for the production of fiber with “mean” diameters in the range of about 2 to 8 μm . This is a two-step attenuation process, involving initial formation of a primary melt stream from holes in the sidewalls of a spinning disc, followed by fragmentation of that melt stream

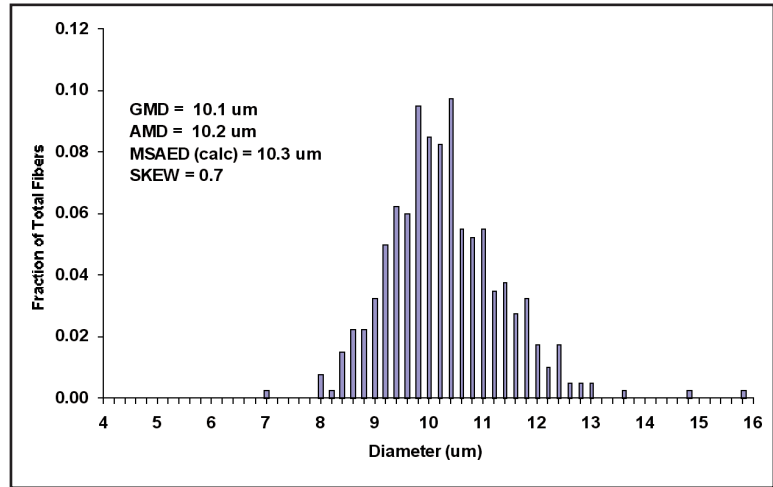


Figure 1

MEASURED (SEM) FIBER DIAMETER DISTRIBUTION FOR NOMINAL “10 μm ” CONTINUOUSLY-DRAWN PRODUCTION FIBER. GMD = GEOMETRIC MEAN DIAMETER, AMD = ARITHMETIC MEAN DIAMETER, MSAED¹ = MEAN SURFACE AREA EQUIVALENT DIAMETER, SKEW = SKEWNESS.

¹ MSAED (mean surface area equivalent diameter), is effectively the diameter of a single fiber with surface area equal to the surface area of the collective sample. It can be derived directly from measured BET data ($\text{MSAED} = 4/\rho \cdot A_s$) or calculated from data from individual fiber measurements (d_i); here $\text{MSAED} = (\sum(d_i^3/n))^{1/2}$. A_s is the BET-determined specific surface area, ρ is the glass density, and n is the total number of fiber counts.

in an air or hot gas jet [2, 3]. While the distribution of “primary” fibers exiting the spinner may be quite normal as in *Figure 1*, the end product distributions are distinctly log-normal, typical of processes where mechanical force has been used to break up and comminute a pre-existing body [4]. As shown in *Figure 2*, this leads to a much broader distribution of fiber diameters with pronounced positive skews.

Important “signatures” of a rotary spun product, besides the relatively broad, log normal distribution are the presence of a small but significant number of large fibers at the high end tail of the distribution and the pronounced drop off in diameter toward the fine end of the distribution. Both reflect the efficiency of the rotary spinning process in regard to complete fragmentation of the primary melt stream exiting the spinner. In this case, more energy per gram of glass would be required to break apart the primary filament more completely.

Note that in positively skewed distributions such as this, the mean surface area equivalent diameter (MSAED) is greater than the geometric mean diameter (GMD). Here the d^2 dependencies of the fiber mass drive the calculations, the implication being that there can be many more fine fibers by actual particle count than surface area calculation or measurement might indicate.

As a discontinuous process, rotary spinning produces a

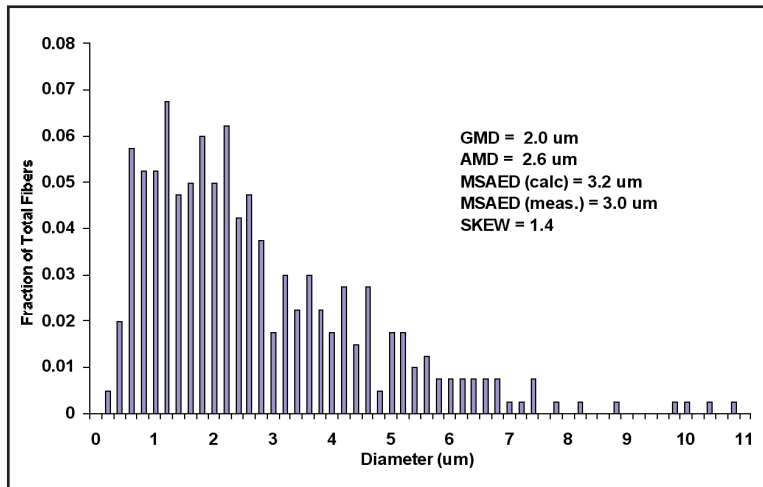
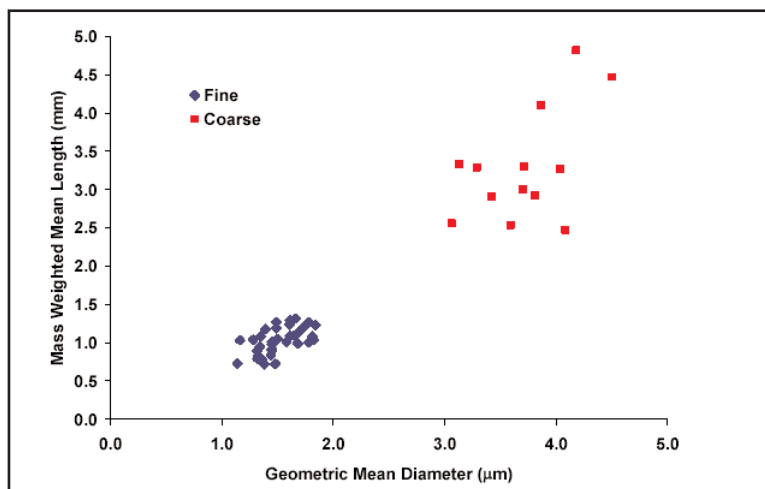


Figure 2
MEASURED (SEM – LINE INTERCEPT) FIBER DIAMETER DISTRIBUTION FOR TYPICAL FINE DIAMETER ROTARY SPUN FILTRATION FIBER

similar log-normal distribution in fiber lengths. Measurement of the latter, however, can be difficult due to the self-entangling nature of discontinuous fiber which can lead to breakage upon attempted separation. Ideally, bivariate analysis (diameter and length on each fiber) by direct measurement of individual fibers is preferred [5], allowing the specific determination of fiber aspect ratio. Difficulties have been documented here as well [5,6], and most frequently fiber length is measured using mass-weighted bulk techniques such as sieve

Figure 3
MEAN DIAMETER - LENGTH CORRELATIONS FOR TWO RS FIBER TYPES. FIBER LENGTH WAS OBTAINED BY WET CLASSIFICATION, FIBER DIAMETER BY SEM (LINE INTERCEPT) MEASUREMENT. LENGTH DATA REPRESENTS AVERAGE OF TWO OR THREE REPLICATES IN GOOD AGREEMENT (ALL VALUES WITHIN 10% OF EACH).



classification of fibers suspended in a flowing water stream.

In RS fiber, we generally see a direct correlation between mean fiber diameter and mean length as shown in Figure 3. The data here represents two product types (“coarse” and “fine”); fiber forming process conditions were varied within each type, producing the variation in fiber dimension. The correlation appears to hold within each group as well as between the two groups.

Flame Attenuation (FA)

As in RS fiberization, flame attenuation involves secondary fragmentation of a primary melt stream or glass “rod”. Use of high velocity - high temperature gas jets impart a great deal of energy into the primary “filament” such that fibers of very fine diameter can be formed. The finest glass filtration fibers are produced in this manner; e.g., geometric mean diameters of FA fibers in production today range from about 0.1 to 5 μm .

However, as shown in Figure 4, there’s quite a difference in “mean diameters”, so it is important to specify which when reporting data or identifying product types. This is the result of an even greater positive skew to the diameter distributions than in RS fiber (compare with Figure 2 – RS fiber with about the same MSAED). This also results in a pronounced “ski-jump” shape to the diameter distributions which is quite characteristic of fibers produced by the FA process.

For microfiber products, MSAED values are usually reported, most often derived from direct BET measurement. Note, again, that geometric means can be considerably smaller. Values can also be strongly measurement dependent, especially if significant variation in fiber length is found. Here, e.g., diameters derived from bivariate analyses can differ from those obtained from length-weighted procedures (typically smaller). As seen in Figure 5, FA fiber lengths generally show a positive correlation with diameter similar to that seen for RS fiber (Figure 3). It is, however, often less well defined in coarser fiber samples. The key difference between the two fiber types lies in the overall fiber aspect ratios (L / D) which are typically considerably greater for FA fiber types. For example, calculating “aspect ratios”² just from data in Figures 3 and 5, we find values for RS fiber ranging from about 500 to 1000, while corresponding ratios for FA fibers

² True fiber aspect ratios are based on collective bivariate data obtained from measurements made on individual fibers. A ratio derived from a mass weighted average value (length) and an average obtained by particle count (diameter) is strictly not correct, however, it is used here as an approximation because of the difficulty in obtaining good bivariate analyses.

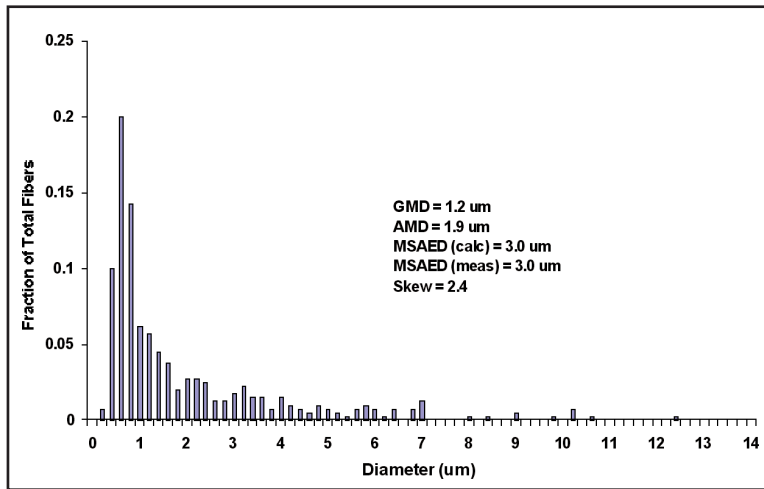


Figure 4
MEASURED (SEM – LINE INTERCEPT) FIBER DIAMETER DISTRIBUTION FOR TYPICAL FINE DIAMETER FLAME ATTENUATED FILTRATION FIBER.

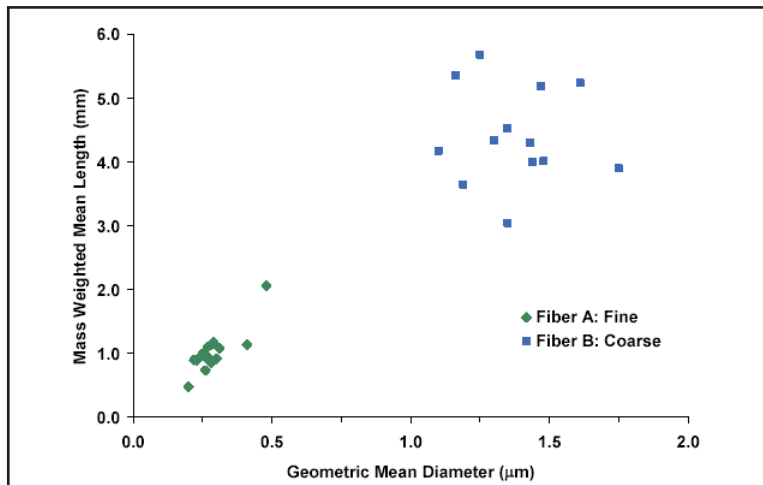


Figure 5
MEAN DIAMETER - LENGTH CORRELATIONS FOR TWO FA FIBER TYPES. FIBER LENGTH AND DIAMETER MEASUREMENTS OBTAINED AS FOR RS FIBER (FIGURE 3).

range from around 2500 to greater than 4000. The FA process allows for much greater attenuation of the primary melt or glass. This is a function of not only process temperatures and times, but also of the particular surface chemistry developed during formation as discussed below.

Role of Fiber Surface

As noted above, fiber dimension and physical properties are dependent upon an interplay of bulk glass composition and process conditions such as temperature, forming and cooling times, and ambient atmosphere that are different

among process types and can be varied by choice of operating parameters within a given process. The unique combination of glass chemistry and forming environment then defines the fiber's surface chemistry which in turn impacts critical end properties [7]. But newly developed surface chemistry can also affect the fiber forming properties as well and thereby the fiber's ultimate diameter and length (in discontinuous fiberization).

For example, in CD fibers, surface chemistry is primarily the result of volatilization losses during forming and cooling rate (for a given bulk composition). Because finer diameter fibers cool faster than coarser ones, there is some range in surface chemistry and surface properties with diameter to be expected. This is, however generally small, as shown previously, e.g., in Table IIa, reference [1]. The rapid cooling of these fibers generally results in high compressive stresses at the fiber surface, so CD fibers usually show the highest tensile strengths for a given diameter.

In RS fibers, the relatively broad range of diameters formed by multiple fragmentation of primary melt streams also means that fibers have cooled at different rates and thereby have undergone different degrees of volatilization and reaction with the ambient environment. This naturally results in a wider range of surface chemistries (e.g., fiber to fiber, or sample to sample when comparing samples of different mean diameter) than seen in continuously drawn fiber. This is also reflected in data presented previously [1]. This in combination with fiber-to-fiber self abrasion, which often occurs in discontinuous processes, usually results in lower fiber tensile strengths per unit length than in CD fibers.

FA fibers are typically those with the highest surface areas and, therefore, would be expected to be those undergoing the greatest impact of fiberization process conditions on their surfaces. As such, it is expected that these finer diameter, higher surface area fibers would show the greatest difference between surface and bulk compositions. This was shown clearly in Table IIa of the previous reference [1]. Note also that flame attenuated fibers can show

the greatest range in fiber surface chemistry when the collection of all products of different mean diameters is considered [1]. Flame attenuated fibers can therefore, show the greatest range of physical and chemical properties – quite valuable if the variability can be controlled through consideration of bulk glass composition and fiber forming conditions.

The importance of fiber surface during formation on ultimate fiber dimensions is shown in Figure 6. Here fiber dimension data for an experimental FA fiber is shown together with previous data from Figure 5. The experimental fiber (C) was developed to match the basic fiber forming properties of Fiber

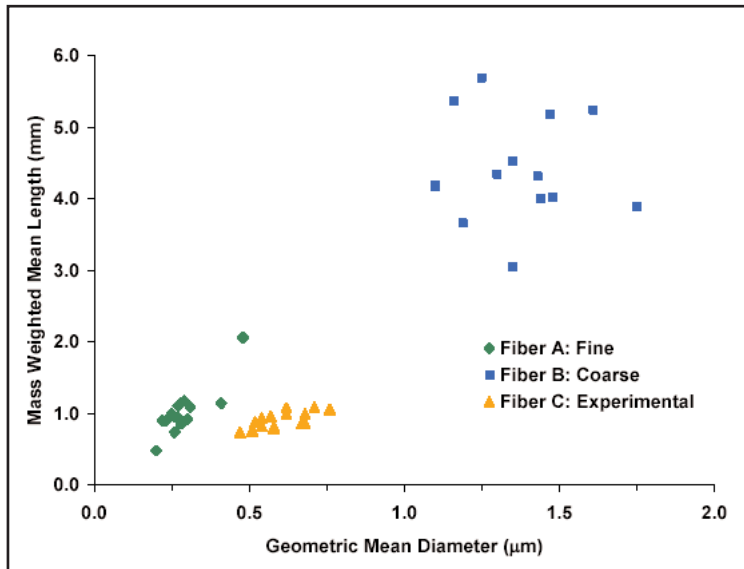


Figure 6

MEAN DIAMETER - LENGTH CORRELATIONS FOR TWO FA FIBER TYPES FROM FIGURE 5 TOGETHER WITH THOSE FOR EXPERIMENTAL FIBER DESIGNED TO REPRODUCE THE ORIGINAL "FINE" FIBER PRODUCT. FIBER LENGTH AND DIAMETER MEASUREMENTS OBTAINED AS FOR RS FIBER (FIGURE 3)

A from Figure 5 (e.g., viscosity – temperature dependence) and therefore was fiberized under the same process conditions as for Fiber A. However, the base glass composition of the two fibers was appreciably different, such that both developed quite different surfaces when interacting with the flame environment on secondary attenuation. This ultimately impacted the degree to which the fiber could be elongated, leading to aspect ratios of only around 1200 to 1700 for the experimental fiber (C) as compared with values of 2500 to 4000 for the original "fine" Fiber A. A much shallower slope to the diameter – length dependency can also be noted.

In the case of Fibers A and C, fiberization process conditions acted differently upon the two bulk glass compositions to modify key forming variables. An example of this is illustrated in Figures 7 a and b which show the effect of process temperature and ambient water content on melt surface tension – an important variable controlling fiber elongation. Note here that the surface tension of the melt comprising fiber A is quite process dependent – e.g., fiberization under conditions of moderate temperature, but relatively low available water concentrations per unit surface area resulted in a significant lowering of melt surface tension to under 300 mN / m, allowing the fiber to be drawn thinner and longer (higher aspect ratio). Correspondingly, Fiber C's composition is rather process insensitive, and no such advantage could be realized – fibers were formed by pulling melts of relatively high surface tension leading to larger diameters and shorter lengths. Since

fibers of higher aspect ratio typically produce stronger non-woven products, this is an important consideration.

The other critical effect of process – composition interactions is on the resultant durability of the glass fiber surface. This can also be predicted from data similar to that shown in Figure 7. I.e., knowing key process variables such as fiber forming temperatures, forming rates, ambient H₂O contents, and quantities of other reactive species in contact with the newly forming fiber surface, it is possible to project properties such as final fiber surface chemistry and density that have a controlling influence on chemical durability. As seen in the case of surface tension (a forming variable), end property variables such as durability also reflect various degrees of "process sensitivity" as a function of initial glass chemistry.

A somewhat extreme example of this is shown in Figure 8 for an experimental glass fiber ("D"). Here the variability in silica content of the fiber surface can be seen as a function of the same two process variables shown in Figure 7. This glass composition is quite process sensitive as seen by the shape of projected silica surface. Surface chemistries and properties will be appreciably different for CD, RS, or FA fibers made from this bulk glass. The benefit of working with a glass of this type is that a wide range of fiber properties can be obtained from one base composition. The downside, of course, is that compositions such as this can be too process sensitive, requiring very tight control on process variables to produce consistent product.

Conclusions

Formation of glass fibers used in filtration applications can be quite complex. Consideration of both initial glass chemistry and fiber forming conditions must be accounted for if tight control of both fiber dimension and fiber surface properties is to be achieved. This can be done with detailed knowledge of how process variables and initial glass chemistry interact. This can lead to new opportunities for glass filtration fibers, e.g., through production of fibers with more controlled dimensions and "engineered" surface properties.

References

1. Bauer, J. F., "Glass Fiber Surface Properties: Influence of Composition and Process", Proc. 1999 TAPPI Nonwovens Conf., Orlando (1999).
2. Rowe, J. G., and Mohr, W. P., "Fiber Glass", *van Nostrand Reinhold*, New York (1977).
3. TIMA, Inc., "Man-Made Vitreous Fibers: Nomenclature, Chemistry, and Physical Properties", North American Insulation Manufacturers' Association (1993).
4. Iler, R. K., "The Chemistry of Silica", Wiley-Interscience, New York, (1978).
5. Lifshutz, N., "The Simultaneous Measurement of Diameter and Length in Glass Microfiber", Proceedings of

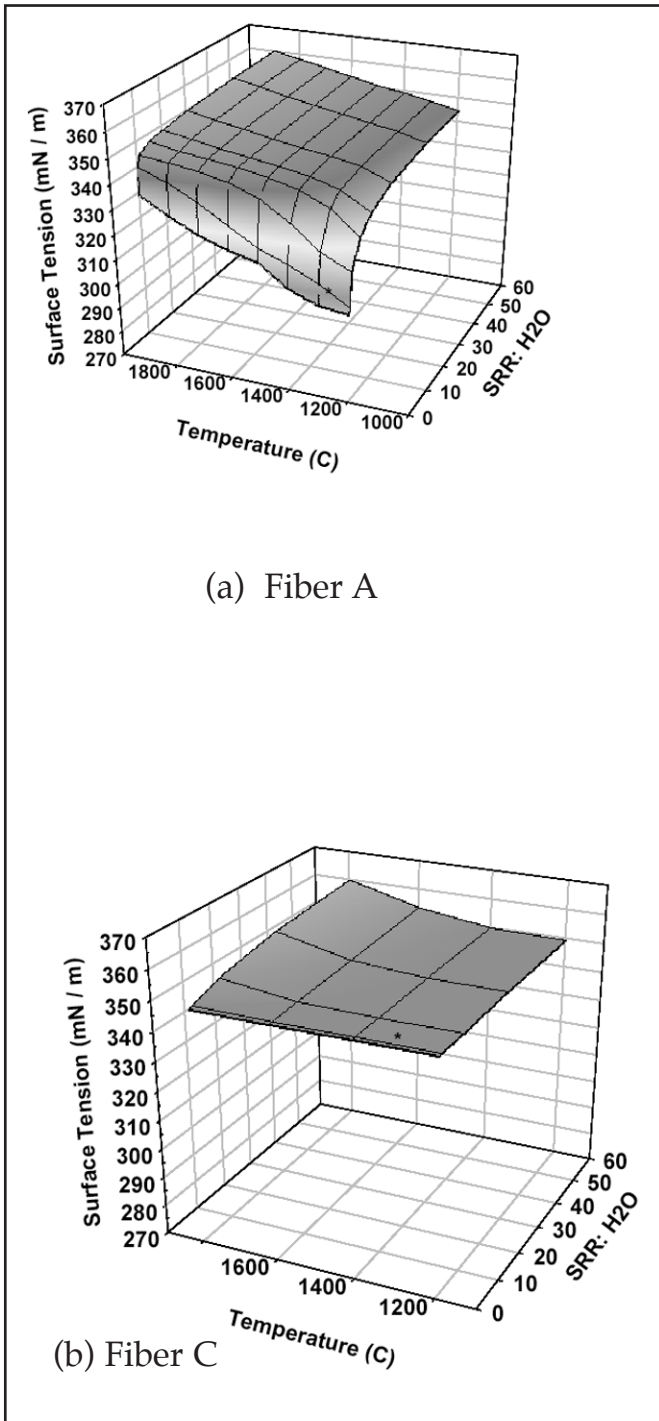


Figure 7

EFFECT OF FIBERIZATION PROCESS CONDITIONS ON MELT SURFACE TENSION FOR TWO GLASS COMPOSITIONS. SURFACE TEMPERATURE AND SURFACE MOLAR RATIO OF H₂O TO AMBIENT GLASS PER UNIT TIME (SRR:H₂O) WERE CALCULATED FROM AVAILABLE DATA. * INDICATES OPERATING CONDITIONS (IDENTICAL IN BOTH CASES) PRODUCING FIBERS WITH DIMENSIONS GIVEN IN FIGURE 6.

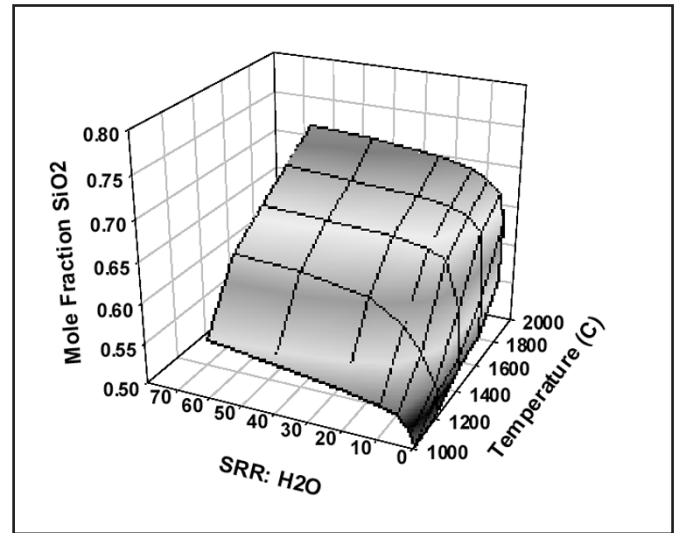


Figure 8

EXPERIMENTAL FIBER D: VARIATION IN CONTENT OF SILICA AT THE SURFACE AS A FUNCTION OF SURFACE TEMPERATURE AND AMBIENT WATER CONTENT DURING FIBERIZATION

INTC 2001, INDA/TAPPI, (2001).

6. Christensen, V. R., Eastes, W., Hamilton, R. D., and Struss, A. W., "Fiber Diameter Distributions in Typical Mineral Wool Insulation Products", *Am. Ind. Hyg. Assoc.*, 54 (5), 232-238 (1993).

7. Bauer, J. F., "Effect of Fiberization Process on Glass Fiber Surfaces", *Ceram. Trans.*, 82, 187-201 (1998). — INJ