April 6, 1965 T. A. GARDNER 3,176,412

MULTIPLE NOZZLE AIR BLAST WEB DRYING

Filed Jan. 4, 1961 4 Sheets-Sheet 1

Fig. 1

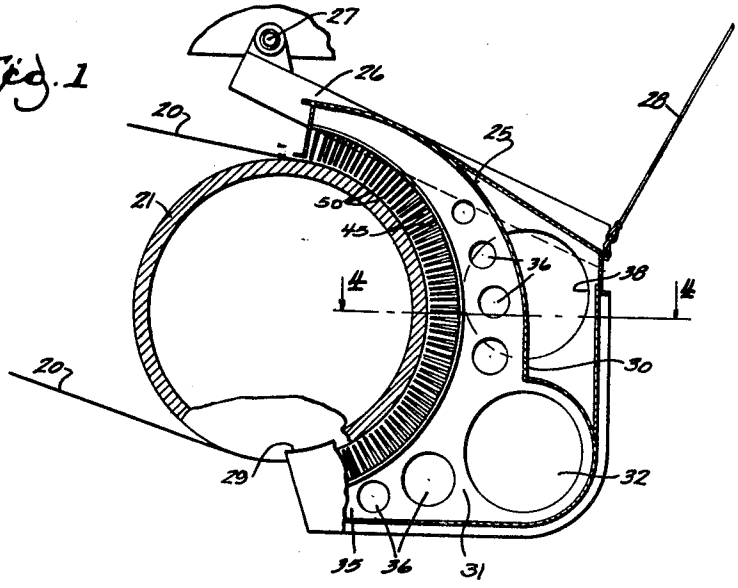
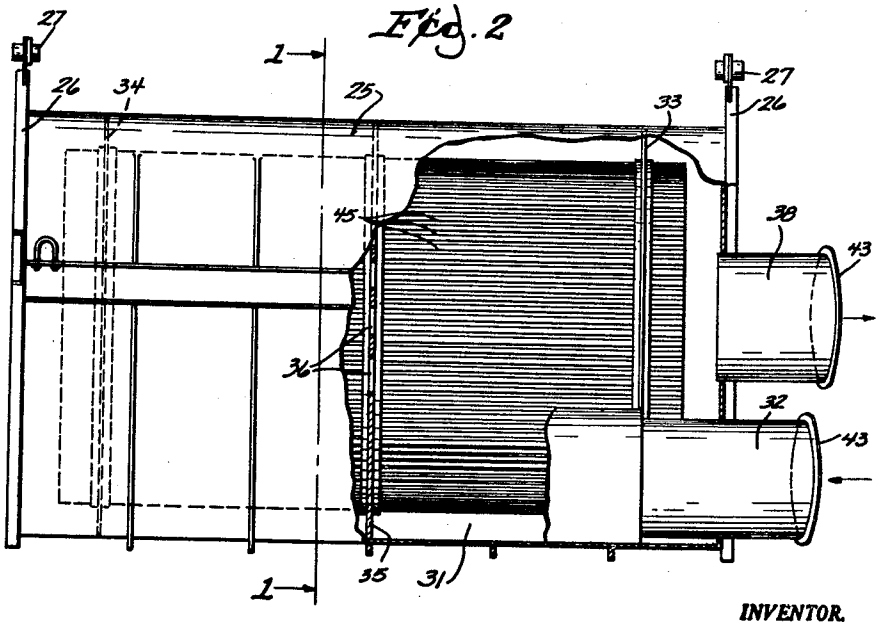



Fig. 2




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Filed Jan. 4, 1961 4 Sheets-Sheet 2

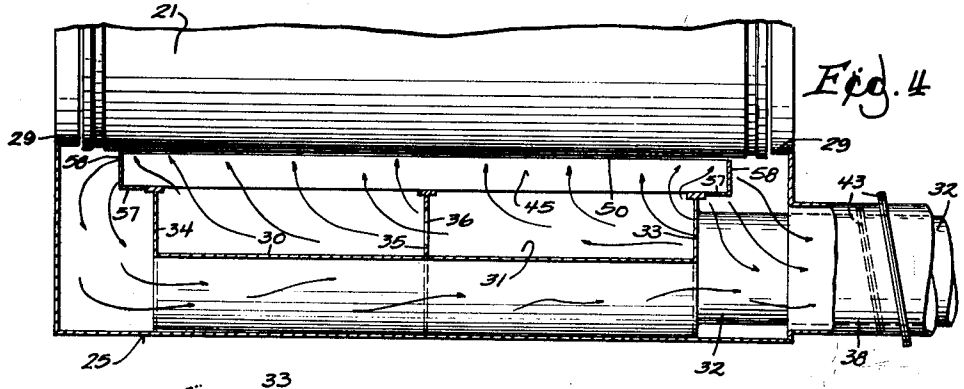



Fig. 4

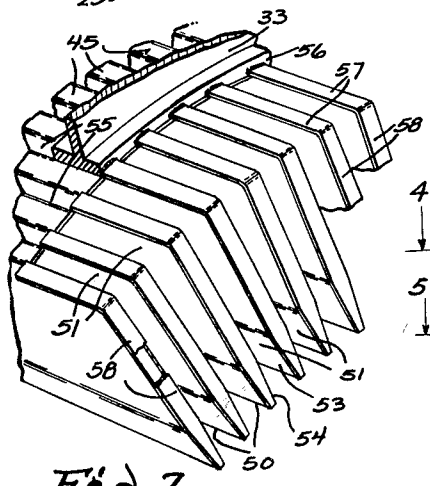



Fig. 7

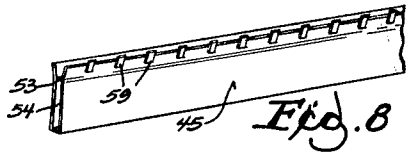



Fig. 8

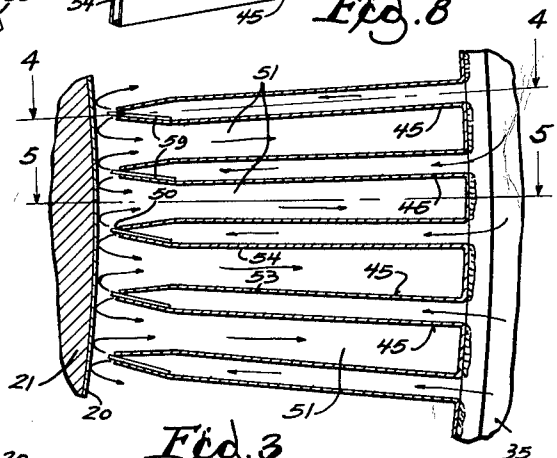



Fig. 3

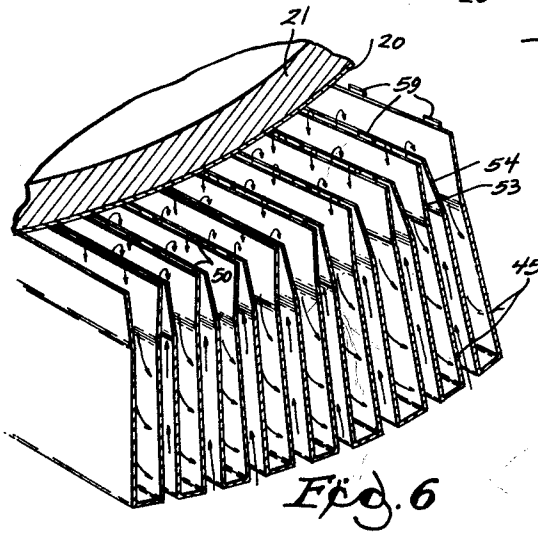



Fig. 6

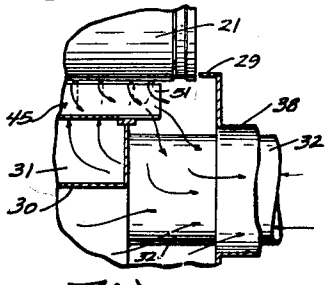



Fig. 5

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April 6, 1965 T. A. GARDNER 3,176,412

MULTIPLE NOZZLE AIR BLAST WEB DRYING

Filed Jan. 4, 1961 4 Sheets-Sheet 3

Fig. 9

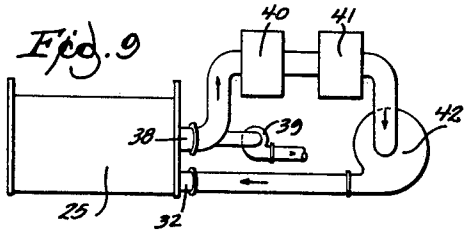



Fig. 11

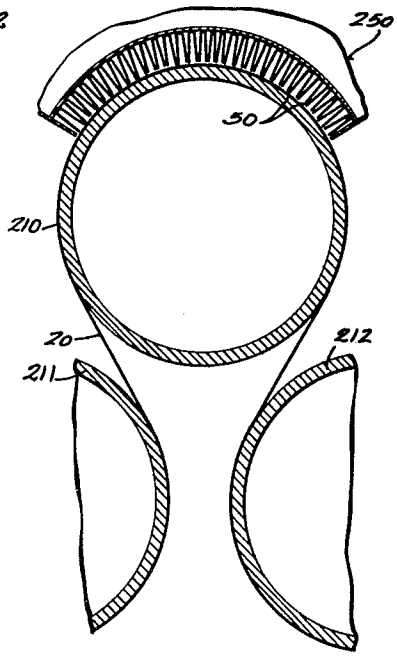
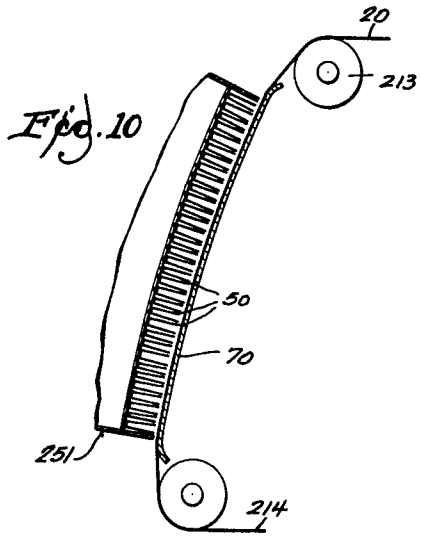



Fig. 10



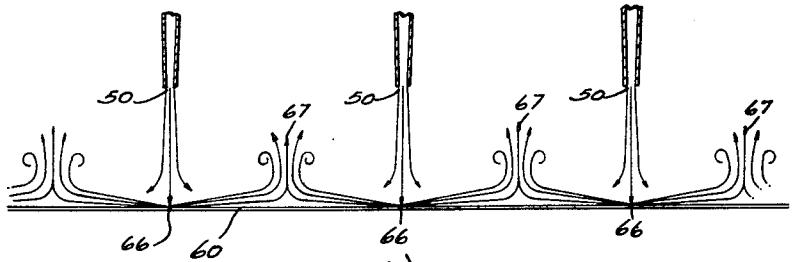




Fig. 12

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MULTIPLE NOZZLE AIR BLAST WEB DRYING

Filed Jan. 4, 1961 4 Sheets-Sheet 4

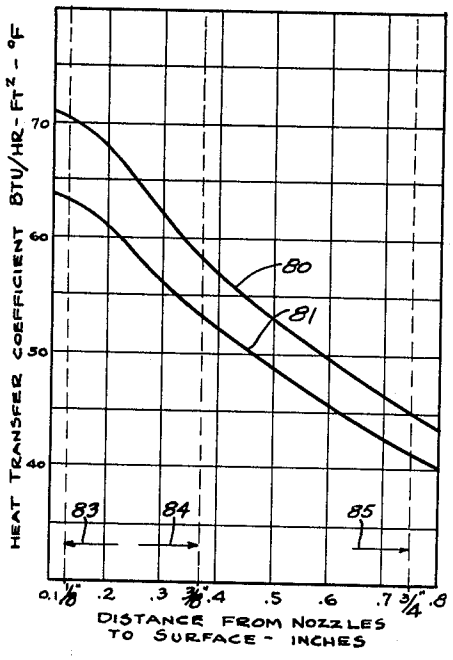



Fig. 15

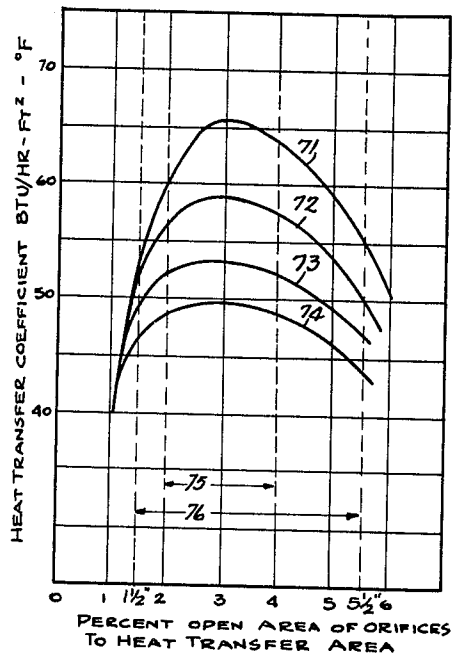



Fig. 16

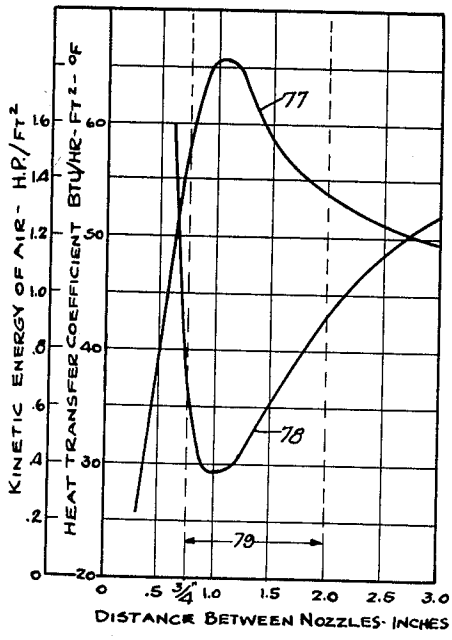



Fig. 17

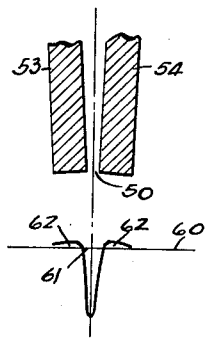



Fig. 13

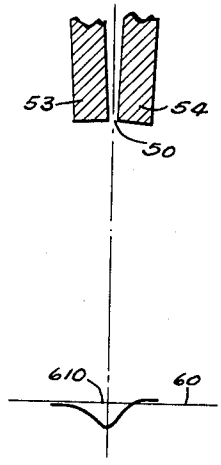



Fig. 14

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3,176,412

# MULTIPLE NOZZLE AIR BLAST WEB DRYING

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Filed Jan. 4, 1961, Ser. No. 80,610
8 Claims. (Cl. 34—122)

This invention relates to multiple nozzle air blast web drying and is a continuation in part of application Serial No. 662,891, filed May 31, 1957, now abandoned, and application Serial No. 743,437, filed June 20, 1958, now abandoned.

The invention seeks to provide increased drying capacity by operating at low Reynolds number values upon the laminar boundary layer of air and vapor in immediate proximity to the web to be dried. (Any drying gas may be used, the term "air" being employed generically since air is the gas most commonly used for drying.) The invention has been tested successfully in the drying of webs of newly-formed paper, the drying of paper coatings, and the drying of inks, dyes and the like on the surface.

While it is convenient to refer to the nozzles which create the jets, it should be noted that it is the jets of dehydrating gas that do the drying and are required to have the critical dimensions and spacing. Thus the figures given above may be stated in terms of the jets themselves. The jets should be spaced from each other not less than three-quarters of an inch nor more than two inches. They should originate at a distance of no more than three-quarters of an inch and preferably one-eighth to three-eighths of an inch from the surface of the work to be dried. The jets should have a total cross section at the said distance of origination which amounts to one and one-half percent to five percent of the area acted upon, the preferred percentage area being two to four percent.

The invention provides increased drying capacity by operating on the boundary layer film in immediate proximity to the web being dried in such a manner that its resistance to the flow of heat and mass is reduced.

The invention is based on critical relationships of nozzles including specifically the ratio of total orifices area to total work area; nozzles spacing from the work to be dried; and the spacing of the nozzles from each other. The distance between nozzles is particularly critical. It should be not less than ¾ of an inch nor more than 2 inches, with peak performance at a space slightly in excess of one inch. The percentage of total area of nozzle orifice to the total heat transfer area of the surface acted upon should be not less than 1½% nor more than 5½%, with a preferred range from 2 to 4%. The distance of the nozzle from the surface of the work is less critical but should be between ⅛" and ⅜" for best results. The dryer shows no improvement over previously known dryers if this spacing is increased beyond ¾ of an inch.

The invention further seeks to provide equal drying across the entire width of continuous webs used in industry. Only if drying is uniform is it possible to operate at high temperature. The large flow area in the preferred plenum compared to the flow area of the orifices ensures that the pressure drop in the orifices will exceed by many times the pressure variations in the plenum. Thus the flow through all orifices is extremely uniform. Uniform drying across wide machines is difficult to maintain. Performance of the machine herein disclosed is very superior.

The invention also provides more economical drying by the conservation of heat and power ordinarily used in drying.

A major complaint made with respect to previously known dryers is the massive loss of air into the room in which the dryer operates. On virtually all dryers, 50% more or less, of the discharge from the first nozzle and the last blows out into the atmosphere after impinging on the surface, because of its high energy. Because of the multiplicity of small capacity nozzles used in the present dryer, the percentage of air lost to the room becomes very small. In the present dryer the air loss with nozzles 1 inch apart is only one third as great as the loss from a dryer of equal size and air capacity with nozzles 3 inches apart.



The matter of air loss is important. Such air carries away both heat and vapor. With small air loss the dryer may be operated at high temperatures and humidities. High humidity operation requires less air to be heated to secure the same amount of drying. Thus the thermal efficiency is high. High humidity also provides high concentration of latent heat, which is easier to reclaim if desired. In the present dryer heat reclamation is economically feasible; formerly this has not been true. In the drying of costly solvents, high solvent humidity permits easier reclamation of the solvent.

There is a further advantage of the present dryer in that it accomplishes a given drying job in very much less space than is required by any previously known machine of comparable capacity. This not only reduces the demands on floor space in the building in which the dryer is used, but it reduces heat losses attributable to radiation and convection.

Another advantage of using very small cpacity nozzles with high jet energy is to provide the beneficial effect of high velocity flow without high kinetic energy such as might disrupt fragile webs or unstable surface coatings.

In practice, the web may be supported either by a relatively flat plate or by a drum or floated between opposed sets of drying nozzles. The speed of the web is broadly immaterial since the flow of drying air is preferably at a rate so high as to make conventional rates of web movement immaterial.

It is conventional to use heat in the drum or plate over which the web is trained for drying purposes. In the use of the present invention, evaporation of moistures or other evaporized liquids will occur so rapidly from the surface of the web as to make it possible to increase the amount of heat used in the drum, at the same time eliminating by evaporative cooling the difficulties experienced in some dryers when the heat is excessive for the particular materials involved.

Laterally elongated non-circular nozzles preferably extending the full width of the web are so organized that the jets of drying gases issuing from the nozzles are directed against the web substantially at right angles to its surface or at an angle which, allowing for web movement, results in a pattern of flow and pressure gradient which is substantially symmetrical from the stagnation point opposite each nozzle. Each nozzle may provide a substantially continuous opening which is as long as the width of the web, broken only by spacers which maintain its side margins at uniform distances.

A feature of the present invention is the provision of means for the escape from the vicinity of the drying surface of air which has been spent in impinging on the surfaces, the escape being accomplished without impairing the uniform drying effect or in any manner impairing the dried web or its coating, and without limiting the length, width, or number of nozzles. The flow of impinged drying air along the surface acts as a curtain which isolates the surface from the spent air. The arrangement becomes possible because the escape passages can be small due to the relatively low volume of air admitted through the nozzles. When the web is very wide, escape passages may be provided at the center of the nozzles, as well as at the ends thereof.

To provide a multiplicity of nozzles with their respective pressure gradients extending across the entire width of a web trained over a heated drum results in holding the web more tightly to the drum, air and vapor being purged from the space between the web and the drum, thereby increasing heat flow from the drum to the web. Also the mass transfer rate of vapor away from the web is increased and the vapor pressure and the related saturation temperature on the surface of the web are reduced, thereby increasing heat flow from the drum to the web and making it possible to use higher drum temperatures without "blowing off" the web. The vapor mass transfer coefficient is proportional to the heat transfer coefficient.

There are essentially three primary features of the apparatus. They are:

(1) The spacing of the nozzles from the web.

(2) The spacing of the nozzles from each other, and

(3) The area ratio of the nozzle orifices to the total area of the work exposed thereto.

The spacing of the nozzles from the web should be as small as is practicable. The maximum is critical and should not exceed three-fourths of an inch. Spacings of one-eighth to one-half of an inch have been used successfully, the preferred range being one-eighth of an inch to three-eighths of an inch. There is no advantage in approaching closer than one-eighth of an inch, even if it were practical to do so. The nozzles cannot be brought so close to the work that contact might occur through irregularities in mechanical tolerances. Neither can the nozzles be withdrawn from the work substantially beyond one-half inch without largely destroying the advantage which this apparatus has over conventional dryers. Any loss of velocity at the point of impingement of the drying gas on the surface of the work can be compensated only by increased power.

Whatever the kinetic energy of the air in any particular installation, the nozzle arrangement disclosed herein will produce at least thirty percent more heat transfer with correspondingly increased mass vapor transfer than can be achieved in any drying organization which does not employ the arrangement of the present invention.

Nozzle spacings up to two inches are practical. However, there are marked advantages if a spacing closely approximating one inch is used with the preferred area ratio of nozzle orifice to total area. The relationship between the open area of the nozzle and the total heat transfer area of the work upon which the jets from the nozzle is operating is very important. As shown by the charts included in the drawings, the percent of orifice area should be approximately three percent of the heat transfer area at all nozzle spacings, the outside limits being a minimum of one and a half percent and a maximum of five and a half percent with a preferred range of two to four percent.

The drying gas, herein called air for convenience, is supplied to the nozzles at such pressure as to produce very high velocities, a preferred range being 10,000 to 20,000 feet per minute.

Since the volume delivered from the very narrow nozzles is small, the power requirement is not excessive and the kinetic energy expended on the surface of the web is not destructive. The small volume flow from an individual nozzle has little energy in spite of the high velocity of the jet.

The net result of these factors is to disrupt the laminar boundary region with high frequency to promote high heat and mass transfer rates.

A convenient mechanical construction involves the connection of the bases of generally channel-shaped members with slightly flared sides to the otherwise open side of a plenum chamber so that the bases of the respective channels close the chamber except for nozzle openings between the opposing and outwardly converging side walls of consecutive channels. Thus the nozzles are constituted by these opposing side walls and the interior spaces of the respective channels open at their ends to permit the escape of the vapor bearing air. In a preferred organization the air is recirculated through a filter and heater with controlled continuous withdrawal of some of the saturated air and its replacement with unsaturated air. There is nothing fundamentally new about recirculation but, as will be shown hereafter, the drying results produced by the instant invention are very greatly superior to the drying achieved with any other known device for the purpose.



In the drawings:

FIG. 1 is a view taken in section of FIG. 2 through a typical installation.

FIG. 2 is a view in rear elevation of the device shown in FIG. 1, portions of the housing being broken away.

FIG. 3 is a greatly enlarged detail view of some of the nozzle structure shown in FIG. 1.

FIG. 4 is a view showing the drum in side elevation and the nozzle structure in section on line **4—4** of FIG. 1, the section also being indicated at **4—4** in FIG. 3 to show that it passes through one of the nozzles.

FIG. 5 is a fragmentary detail view taken in section on the line **5—5** of FIG. 3.

FIG. 6 is a fragmentary view in perspective of the apparatus as it appears from the inner ends of the nozzles, portions of a roll and the web to be dried being fragmentarily illustrated.

FIG. 7 is a view in perspective fragmentarily illustrating the ends of a bank of nozzles and the adjacent end wall of the plenum chamber, all of the air collecting chamber walls being broken away.

FIG. 8 is a view in perspective of a fragmentary portion of one of the individual troughs that make up the nozzle bank.

FIG. 9 is a diagrammatic view on a reduced scale showing the circulatory system.

FIG. 10 is a view in cross section showing a modified application of the invention to a web passing over a fixed plate.

FIG. 11 is a diagrammatic view in cross section through a series of drying rolls to one of which a bank of drying nozzles embodying the present invention has been applied.

FIG. 12 is a diagrammatic view showing the effect of the jets of drying gases produced according to the invention.

FIGS. 13 and 14 are pressure charts showing the comparative effect of locating the nozzles at different distances from the work.

FIG. 15 is a chart showing the effect of the distance of the nozzle from the surface of the work.

FIG. 16 is a chart showing the effect of total orifice area in relation to the total heat transfer area of the work.

FIG. 17 is a chart showing the effect of distance between nozzles upon the heat transfer coefficient and upon the kinetic energy of air required to produce a given rate of heat transfer.

In the embodiment shown in FIGS. 1 to 9 the work to be dried is represented by a web **20** passing about a drying roll **21** which may be assumed to be the steam-heated roll of a conventional dryer to which the drying apparatus of the present invention has been added. As already noted, the invention is not concerned either with the material of the web or the liquid to be vaporized. The invention is applicable to primary drying which involves the removal from a freshly formed paper web of the liquid component of the furnish. It is also applicable to machine felts and to crepe. It has been tested in the drying of the printing done by a four-color rotary printing press. It is also usable to preset aqueous coatings and to remove the volatile constituents of coatings, inks, and dyes. The foregoing particulars are given by way of example and not by way of limitation. Also, because air is the most readily available drying medium, the invention will be described with reference to air but with the under-

standing that other drying gases are equivalent so far as the present invention is concerned.

For convenience, the entire apparatus is mounted within a hood or shroud 25 bodily movable to and from the roll 21 which not only provides a platen for the support of the web but also desirably contributes heat to expedite the drying. One way of mounting the hood for advancing and retracting movement is to support it on the arms 26 from trunnions 27 about which it may be withdrawn pivotally from the drum by cables 28 to facilitate training the web about the drum, or to give access to the nozzles when cleaning is desired.

The rim 29 about the margin of the hood is in proximity to the periphery of the drying cylinder 21 but is usually spaced about one-half inch from the end of the cylinder and about one-half inch radially inwardly from the surface of the cylinder. This rim reduces the area through which fresh air is drawn into the system thereby providing more effective seal. It also serves to deflect the stream of air flowing out of return spaces between the nozzles hereinafter described.

Within the hood 25 is an inner wall 30 which provides a plenum chamber 31 to which the drying air is admitted through pipe 32. The plenum chamber is shorter than the hood, its end walls 33, 34 being spaced from the ends of the hood. Support for the nozzles is provided by the walls 33, 34 and by an intermediate partition or partitions 35 provided with a sufficient number of apertures 36 to permit ready flow of air throughout the plenum chamber from one end to the other. The plenum chamber is so sized that the cross sectional area of flow at any point is considerably greater than the total orifice area downstream of the point. This arrangement provides uniform distribution of air to all nozzle orifices if air is supplied under some pressure to the plenum. Since the orifices represent but a small open area the pressure plenum need not be excessively large.

The internozzle channels, hereafter described, lead the saturated air from the surface of the web to the ends of hood 25, externally of walls 33 and 34. From this external space the air is exhausted through a pipe 38. Some of it is discharged through the blower 39 and replaced by make-up air which leaks in to the extent that circulating air is discharged. The rest passes through a filter 40 and heater 41 and is recirculated by blower 42, which delivers the air back into the pipe 32. Desirably, the return air temperature may be about 300° F. and its pressure sufficient to develop a flow through the nozzles at the rate of about 16,000 f.p.m. This head is about 16" water gauge presure at 70° F.

The two pipes may have beveled flanges at 43 which seat with complementary flanges of the circulatory pipes when the housing is lowered to the operative position of FIG. 1. The seated connection is shown in FIG. 4 and the flanges separately in FIG. 2.

The inner wall of the plenum chamber 31 is composed entirely of the eighty-four channels 45 which in practice have been used to form the respective nozzles 50 and the vent spaces 51 as best shown in FIGS. 3, 6 and 8. The number of channels is, of course, optional, depending on the size of the bank of nozzles. The bases of the respective channels are welded to the bulkheads or partitions 33, 34, 35 as shown in FIG. 3. As already indicated, the otherwise generally parallel side walls 53, 54 of the respective channels 45 flare slightly adjacent their ends and the proximate side walls of consecutive channels converge to form the nozzles 50. While not critical, the included angle between the converging side walls which form the nozzles 50 has been made about 20°. It has been found that the change in angle between the generally parallel portions of the side walls and the converging portions 53', 54' stiffens the nozzle and there is less friction loss in the nozzle than would be the case if the side walls converged uniformly from the bases to the ends.



These nozzles are spaced from each other three-fourths of an inch to two inches or desirably about one inch center to center. Importance of nozzle spacing is clearly shown in FIG. 17 which demonstrates that the spacing is critical, the permissible range being three-fourths of an inch to two inches and the greatly preferred spacing being very close to one inch.

FIG. 17 shows the effect of distance between nozzles when the nozzles are mounted one-fourth of an inch from the work surface, the orifice openings aggregating 2.8 percent of the exposed surface and the air temperature being 400° F. The curve 77 shows the heat transfer coefficient at various nozzle spacings with air energy of 0.4 H.P./ft.$^2$. The curve 78 shows kinetic energy of air required to maintain a heat transfer coefficient of 65 B.t.u./hr. ft.$^2$ ° F. The preferred range of operation is at nozzle spacings between the broken lines indicated by the arrow 79. The area between nozzles can be kept small so that the velocity of the exhaust air is quite high, this being permissible because the path of flow of the discharge air and vapor is isolated from the drying surface by the dynamic air curtain along the surface produced by the high velocity nozzle discharge.

It has also been found practicable that each nozzle have an opening approximately .023 inch wide and ten feet four inches long interrupted by spacers hereinafter referred to. However, while the dimensions are critical within limits hereafter explained, the specific dimensions here given are merely illustrative.

The relationship between nozzle opening and nozzle spacing can be expressed in terms of a ratio of nozzle opening to heat transfer area. The total orifice area should be not less than one and a half percent or more than five and a half percent of the heat transfer area, the preferred range being two to four percent for reasons clearly shown in FIG. 16.

In FIG. 16 the curve 71 shows the heat transfer coefficient in relation to the percentage of orifice area to heat transfer area when the nozzles are spaced one inch apart, the air energy being constant at 0.4 H.P./Ft.$^2$. The curve 72 is a similar curve showing the relationship when the nozzles are spaced one and a half inches apart. The curve 73 is based on a nozzle spacing of two inches and the curve 74 is based on a nozzle spacing of three inches from each other.

The preferred range of percentages lies between the broken vertical lines indicated by the arrow 75 while the broken lines designated by arrow 76 show the outside limits within which practicable operation according to the invention is achieved.

As best shown in FIGS. 2 and 7 the respective channels 45 extend beyond the respective plenum chamber end walls 34, 35. The spaces 55 leading to the nozzles 50 are closed off outwardly of the end wall flange 56 by plates 57, 58 welded between the outer margins and ends of side wall portions 53, 54 of successive channels. To facilitate the escape of saturated air from the vent spaces 51, the bases of the channels are cut away beyond the end wall flanges 56 as best shown in FIG. 7.

Each of the channels is provided at intervals along one of its flared side walls with the spacers 59 which are shown, by way of example, applied to the side wall 54 of the channel 45 separately illustrated in FIG. 8. It is practicable to use spacers 3/32" in width and 2½" center to center. When the several channels 45 are assembled in a bank, as shown in FIGS. 1, 3 and 6, their opposing side walls 53, 54 converge to form a narrow nozzle slot 50, the width of which is determined by the spacers 59. The spacers should be present in the minimum number required to support the margins of side walls at the desired spacing. The spacers facilitate assembly. They may comprise weld metal and later are securely fused to the side walls at the tips of the nozzles by a spot welding operation, without, however, appreciably changing the desired orifice opening. The length

of the spacers is so slight that they do not materially affect operation. Thus the effective length of each nozzle is desirably at least equal to the width of the web to be dried.

The desirable range of nozzle opening widths in relation to work area has been found to be .015 to .055. In practice, these tend to lie within the range of .020 to .030. The opposed side walls **53** and **54** of consecutive channels constitute the nozzle and then converge with an angle up to 20° between them. Actually an angle of 3° or 4° is satisfactory. This angle is not critical but is largely a matter of design, the jet expansion angle being independent of nozzle design.

The nozzles **50** are located in very close proximity to the web. The preferred range of spacings is from one-eighth of an inch to three-eighths of an inch, although spacing of one-eighth of an inch to one-half of an inch have been used successfully. FIG. 15 shows that beyond three-fourths of an inch there is no advantage over conventional dryers.

FIG. 13 is a chart showing actual measurement of surface pressures exerted by a blast of air under 12.2" water pressure issuing from a nozzle .015" in width spaced one-eighth of an inch from a surface **60**. The line **60** not only represents the surface but represents the zero pressure.

As shown in FIG. 13, the area **61** in which the work surface **60** is subject to near-maximum pressure is only slightly in excess of the nozzle width and the pressure over this area is quite high, being nearly equal to the stagnation point pressure at the apex of the curve. From this maximum the pressure falls off sharply to subatmospheric pressure in the areas **62** at each side of the pressure area. The sharp reduction is important because it results in a very steep pressure gradient along the surface of the work in the plane of the laminar boundary layer. This tends to subject the molecules constituting the laminar boundary layer to greater fluid shear, thereby increasing the rate of molecular flow in a direction such as to make the boundary layer thinner and increase the rate of heat exchange and of drying.

With the nozzles spaced in accordance with preferred practice, the resulting flow is as shown in FIG. 12, the maximum continuum along the surface between consecutive nozzles being no greater than half the distance between nozzles symmetrically in both directions from the point **66** of impact to the intermediate areas of escape as indicated by the arrows **67**. This is important in view of the analogy hereinafter made to the Pohlhausen theory of heat transmission through the boundary layer and because it means that every part of the work surface is constantly being exposed to fresh and unsaturated drying air whereas previous dryers have developed a pattern of flow in which the continuum is practically coextensive with the entire surface.

Comparison of FIG. 13 with FIG. 14 shows the difference in pressure curve resulting from spacing the nozzle one-half inch from the work surface instead of one-eighth inch, everything else being the same. It will be noted from FIG. 14 that there is no longer any area of sub-atmospheric pressure such as that shown at **62** in FIG. 13. The area **610** which is subject to superatmospheric pressure is much broader due to the expansion of the jet from the nozzle. (The expansion angle is about 6½°.) For the same reason the pressure is also much less. However, evaporation is still several times as great as in the use of techniques previously known.

The removal of the nozzle beyond three-fourths of an inch from the surface so far diffuses the jet and reduces its pressure as to result in a drying loss so great in relation to the gains otherwise found in the use of this invention as to make it impractical to operate with the nozzle at a distance in excess of three-fourths of an inch from the work. See FIG. 15. The preferred range is one-eighth of an inch to three-eighths of an inch as shown by the vertical broken lines identified by arrows **83** and **84** in FIG. 15. Arrow **85** designates a vertical broken line representing a distance of three-quarters of an inch of travel of the jets from the nozzles to the work, this being the top of what is regarded as a practicable range of jet travel. FIG. 15 shows the effect of varying the distance between the nozzles and the surface of the work with the air temperature and energy constant. In making these curves, the air was held to a temperature of 400° F. and the air energy was held at 0.4 H.P./ft.². The curve **80** was taken with the nozzles of 0.028 inch orifice one inch apart. The curve **81** was made with the nozzles one and a half inches apart and having openings 0.042 inch.

In the device of FIG. 11 I have shown a whole series of drying rolls **210**, **211** and **212** about which the web **20** is trained for drying. As before, these may be assumed to be the conventional steam-heated rolls of a commercial dryer such as is in general use in paper making. The bank of nozzles **50** in the hood **250** is here placed on the upper surface of the roll **210** instead of about one lateral surface as in the case of the roll **21**. The arrangement is otherwise identical.

In the construction of FIG. 10 the rolls **213**, **214** are mere idlers and the web **20** to be dried is fed over a supporting plate **70** with which the hood **251** is associated. Although the work-supporting platen constitutes the stationary plate **70** instead of a roll such as those indicated at **21** and **210**, the arrangement of the nozzles **50** in a bank within hood **251** is essentially the same and the operation is similar to that above described.

The principles underlying the invention are as follows:

The problem is to remove a vaporizable liquid from the surface of the work which, in this instance, is represented by a moving web. The vaporizable liquid may be present in the web as a result of manufacture thereof or it may be present on the surface of the web as, for example, the result of a coating or a printing operation. Regardless of the depth to which the liquid penetrates the web, the vapor must always be removed from the surface.

Wherever there is relative motion between a surface and a surrounding gas there exists the phenomenon known as a boundary layer resulting from molecular adhesion of molecules of gas to each other and to the surface. In the case of most dryers using air, the boundary layer is turbulent at its surface and is generally considered to consist of three distinct layers or strata, the innermost, close to the surface of the drum, being laminar. Outside of the laminar stratum there is a transition or buffer stratum in which the molecules are less closely bound and outside of this there is a turbulent outer stratum wherein the molecules are bound to the drum but capable of turbulent movement respecting each other. To remove the moisture from the web on the surface of the drum, heat is caused to pass inwardly through the boundary layer and the vapor must move outwardly through that layer. Heat and vapor transfer through the boundary layer is relatively slow due to the insulating effect of the gas. It is desirable to reduce the thickness of the boundary layer and thereby its insulating effect.

In the laminar inner stratum transfer takes place extremely slowly by molecular diffusion. Thermal gradients are very steep. In the turbulent strata particles of fluid do not move in orderly fashion but move in eddies. This action causes rapid diffusion and therefore heat transfer rapidly occurs with relatively low gradients. The inner laminar stratum presents the primary obstacle to the movement of both heat and vapor.

In the past, the effort has generally been to supply substantial volumes of gas at relatively high velocity. However, in such arrangements the velocity has to be limited because, at least in the drying of paper or the like, there is a limit to the amount of velocity and mass

which the paper can stand without displacement of fiber, and even disruption of the surface. By placing the nozzles extremely close to the surface of the work, in accordance with the arrangement previously described, I am able to use higher velocities and lower masses of air in a way to change the characteristics of the boundary layer to maintain a laminar layer which is unusually thin because of its short continuum, whereby to bring about tremendous increases in drying rate without endangering the surface of the work. However, if the nozzles are placed too close together or if the ratio of total nozzle area to treated work area is too large, the flow from adjacent jets mutually interferes so that a sudden loss in drying occurs.

In preferred practice the velocities at the nozzle orifice are in the range of 10,000 to 20,000 feet per minute. However, since the volume of air from each nozzle is small, the amount of power required is not excessive, and at a ratio of nozzle opening to surface area of two to four percent the kinetic energy expended on the surface is within safe limits.

It is also a feature of the present invention that the nozzles are quite close together about the surface of the drum. This is true even though relatively greater space is provided for the exhaust of air and vapor between nozzles than is possible in some of the prior art devices. The advantage of having the nozzles close together is that the more frequently and thoroughly the boundary layer can be disrupted and its saturated air withdrawn, the lower will be the Reynold's number and the greater will be the evaporation rate.

Primary purpose of the nozzle arrangement is to provide high heat and mass transfer coefficients in the film of air on the surface of the material being dried. Since mass transfer in an air film or the capability of the air film to allow evaporation is largely a function of the heat transfer coefficient, the latter will henceforth be used for simplification but with the understanding that it is essentially identified with the drying potential. Furthermore, since most air dryers are capable of being attached to an air circulation system which may provide air or other gas at various temperatures and humidities, the chief criterion of the efficiency of an air dryer is the heat transfer coefficient which depends to a large extent on the geometry of the given dryer.

As has previously been shown, the continuum of the boundary layer with respect to the surface of the web consists of a length or distance originating at a point on the surface directly under the nozzle which is called the stagnation point and continuing to a point on the surface midway between the nozzles. The boundary layer film developed under my nozzle arrangement is highly analogous to the proposition stated by Pohlhausen in his development of a formula applicable to heat transfer to or from a thin flat plate immersed in a deep uniform fluid stream. (McAdams, "Heat Transmission," 3rd edition, page 224.) The chief difference between the Pohlhausen proposition and the case of this dryer is that in the former a uniform flow exists at the origin of the continuum and no pressure gradient exists in the direction of flow, whereas in this dryer a pressure potential exists at the origin which is rapidly converted into high velocity flow with an accompanying steep pressure gradient in the direction of flow. Beyond the point where pressure potential has been converted into high velocity flow and for the greater part of the continuum the analogy is nearly exact.

Little is known about the effect of a steep pressure gradient on the boundary layer.

If a pressure gradient is imposed on the boundary layer in the direction of flow, all particles in the film or boundary layer are subjected to the pressure gradient in addition to the usual viscous drag and pull of vertically adjacent particles. Therefore, in the practice of the present invention, it is believed that there is a region



of very high fluid shear close to the surface in the impingement area. This high shear is believed to be the cause of the very high heat transfer and mass transfer rates achieved by the present invention, as compared with those predicted by the Pohlhausen formula cited in McAdams supra.

I have rearranged the Pohlhausen formula and grouped all of the quantities related only to the internal state of the fluid in a single constant *n*. The formula thus modified is as follows:

$$hmn\frac{V^{1/2}}{L}$$

As in the Pohlhausen formula L represents the length measured from the source of flow over which the heat transfer occurs. In my apparatus L necessarily is equal to one-half the distance between nozzles, since the flow under consideration is the flow between the point of impingement against the work and the point at which the gases and vapor escape from the surface of the work (see FIG. 12).

In the Pohlhausen formula V is the stream velocity which is comparable to the impingement velocity in my apparatus. From this abridged formula it is apparent that a greater heat transfer coefficient, $h_m$, will result with higher impingement velocity and/or shorter continuum length. In the actual measure of heat transfer, I have found that the length L has an even greater effect than indicated by the modified formula—probably due to the high shear effect above referred to.

The impingement velocity is related to the velocity at the nozzle orifice, the size of the orifice, and the distance of the nozzle from the surface. The formula,

$$\frac{V}{\bar{V}}\left(\frac{D}{\alpha Y+\frac{D}{2}}\right)^{1/2}$$

relates these quantities according to my measurements. $V/\bar{V}$ is the ratio of impingement velocity to nozzle velocity with a limiting value of 1.0; D is the width of the nozzle orifice; Y is the distance of the nozzle from the surface. And $\delta$ is a constant with a value of about .13 related to the expansion angle of the jet. It is evident from the formula that increasing the distance of the nozzle from the surface will decrease the impingement velocity, and reducing the nozzle orifice will also decrease the impingement velocity though not to the same degree.

FIG. 15 shows the effect of varying the distance of the nozzle from the surface. As will be apparent, the heat transfer coefficient reaches a maximum at a point near one-eighth of an inch spacing of the nozzle from the surface. The chart shows that there is no material advantage in spacing the nozzle more than three-fourths of an inch from the work. The spacing should preferably be kept lower than three-eighths of an inch.

The effect of varying the orifice opening in percentage ratio to heat transfer area is very clearly shown in FIG. 16 for different nozzle spacings. At all spacings the heat transfer coefficient falls off very sharply below one and a half percent and is seriously impaired above five and a half percent, the preferred percentage range being between two and four percent.

It will be observed that in the above equation it is assumed that the quantity in parenthesis is less than unity. If it were above unity, the equation would cease to have significance from the standpoint of the present invention. Unity is virtually reached with a nozzle .032 in width and spaced from the work by one-eighth of an inch. The formula is verified in FIG. 15. The invention contemplates as one of its requisites that a relatively high impingement velocity of the stream of drying gases against the work, together with the relatively close spacing between such jets of drying gases, be used to reduce the continuum and minimize the thickness of the

laminar portion of the boundary layer which is proximate the work. If the spacing of the nozzles from the work exceeds a value such that the value of the above equation exceeds unity, no further advantage is gained. Thus there is little advantage in spacing closer than about one-eighth of an inch. Ideally the value of unity for this quantity would be desirable.

Note further that it is desirable that the nozzle spacing from the work be several times the orifice width in order that maximum gas velocity will be developed at the impingement point rather than between the nozzle edge and the work.

As compared with competitive equipment my drying apparatus exhibits several advantages not heretofore regarded as possible of achievement. In addition to much greater drying capacity my unit has demonstrated the characteristic of very uniform drying across the entire width of webs up to one hundred eighty inches wide and more. The nature of my design also lends itself to high thermal efficiency, yet requires low power. At any given kinetic energy the described nozzle arrangement has at least thirty percent more heat transfer than any previously known dryer. The character of the curves shown in FIGS. 15–17 will not change substantially at any practical air pressure. However, these figures assume that the nozzles will be of the transversely elongate type herein shown.

My dryer has consistently effected removal from a web surface of vaporizable liquid at the rate of eight pounds to twenty pounds per hour per square foot of surface (depending on the application) by the use of air only, without any other source of heat. One unit has removed sixty pounds of water per hour per square foot of surface in combination with a heated cylinder and there appears to be a possibility of still further improvement.

The previously demonstrated high drying capacity of my apparatus has been successfully proven. In one case the addition of two of my devices to a paper machine dryer section composed of twenty forty-eight inch cylinders increased the drying capacity of the machine in excess of 30%. In another case a new design of rotogravure press with greatly reduced length of draw between decks was made possible by the use of my drying device. In each of these cases and in others the high drying rate in a short space has been a decisive advantage.

The great heat and mass transfer coefficients of my drying apparatus and method have several incidental advantages. When my dryer is used in conjunction with the usual steam-filled cylinder of a conventional dryer, a large portion of the heat required for evaporation is supplied to the web from the surface of the cylinder. In some instances in the prior art the cylinder surface is so hot as to develop high vapor pressure between the web and the cylinder sufficient to force the web away from the cylinder surface, thus sharply reducing heat transfer. The use of my invention so reduces the vapor pressure on the outer surface of the web that the resulting gradient of vapor pressure through the web reduces the tendency for the web to "blow off" the cylinder. Moreover, the increased rate of evaporation from the surface of the web sharply reduces the temperature to which the web is subjected and makes it possible even to increase the amount of heat in the cylinder beyond the point previously thought to be damaging to the web.

The uniformity of drying across the entire width of a web secured in my apparatus is an important result of my nozzle arrangement. The reason that other attempts to obtain high drying capacities have failed to be practical is because they were unable to dry uniformly across the width of webs commonly used by industry. In my apparatus the turbulent mixing of air under pressure in the pressure plenum insures uniformity of temperature and humidity. Since the pressure drop through the nozzle orifice is relatively large, the velocity issuing from the nozzles is quite uniform over the entire drying area. The flow from the nozzles impinges on the surface and is thus redirected to flow on the surface from the stagnation point opposite a nozzle to a point midway between nozzles where the air leaves the surface. This flow of air at high energy on the surface insulates the surface from the effect of spent air leaving the area through the internozzle channels. The surface is therefore contacted only by the primary stream of air at uniform temperature and humidity from the nozzles. The critical test of the uniformity of drying for any air dryer is operation at high temperature since non-uniformity of drying is accentuated by high temperature. In practice my apparatus has dried a web one hundred forty-eight inches wide with an air temperature of approximately 680 Fahrenheit without measurable variation in dryness across the width of the web leaving the dryer.

My device provides high drying capacity and uniform drying, and is at the same time economical to operate. Although it is conventional to use relatively high pressure in the supply to the drying unit, the flow through the nozzles is low, and at the specified ratios of nozzle area to work area, low fan power is required (see FIG. 17). In my apparatus the drying potential varies approximately as the .24 power of the fan horsepower in a given design of the device. Therefore excessive use of power produces little benefit. In practice my apparatus requires air driving power of approximately one-half horsepower per square foot of drying surface with an air temperature of 200° F.

My apparatus lends itself to the conservation of heat in the drying process. The first and last nozzles effectively seal the drying area from the surrounding atmosphere. In so doing half of the flow from each of these nozzles escapes to the atmosphere, but in a drying apparatus such as mine with a relatively large number of nozzles, the percentage of the leakage is very low. The remaining edges of the drying area are sealed by maintaining close clearances between the exhaust curtain and the web support. Thus it is possible to recirculate a large percentage of the drying air without excessive loss. The air exhausted from such a system contains large amounts of vapor which is conducive to high thermal efficiency. Exhaust humidities in excess of .6 pound of water vapor to one pound of air have been measured.

Furthermore, the very compactness of my dryer, doing a given drying job in a very small area leads to high thermal efficiency since losses due to radiation and convection are less per pound of water evaporated.

In practice my dryer can operate with as little as ten percent of make-up air. Typical steam consumption in the use of my invention is 1.25 lbs. per pound of evaporation. My device requires little space, has low heat loss, requires little maintenance, is easy and safe to operate, has high production capacity, and is inexpensive to produce.

I claim:

1. In a web dryer of the type in which the work to be dried is exposed to jets of drying gas, the combination with means for advancing upon a predetermined path the work to be dried of a plurality of nozzles extending continuously for substantially the full width of the work transversely of such path and very narrow in the direction of movement of the work, said nozzles being directed toward the surface of the work to be dried at a distance of not more than three-fourths of an inch therefrom and spaced not less than three-fourths inch and not more than two inches from each other, the ratio of total nozzle orifice area to total exposed work area being no less than one and one-half percent and no more than five and one-half percent.

2. The device of claim 1 in which the nozzles comprise elongated opposing walls and means closing the nozzles at the ends of said walls, the side margins of said walls being angularly convergent to provide nozzle slots greatly elongated as compared with their width, the said

opposing walls of each nozzle being spaced from the opposing walls of adjacent nozzles to provide clearance for the withdrawal of gases from the surface of the work against which jets of drying gas are directed through said nozzles.

3. In a web dryer of the type in which the work to be dried is exposed to jets of drying gas, means for jetting gas upon the work and including a plurality of generally parallel nozzles elongated transversely of the work to be dried and directed toward the surface of the work to be dried and having spaces between them for the escape of gas which has acted upon such work, said nozzles being spaced from the work at a distance of not more than three-fourths of an inch therefrom and spaced not less than three-fourths of an inch nor more than two inches from each other, said nozzles having an aggregate open orifice area totalling between 1½% and 5½% of total heat transfer area.

4. In a web dryer of the type in which the work to be dried is exposed to jets of drying gas, means for jetting gas upon the work and including a plurality of generally parallel nozzles elongated transversely of the work to be dried and directed toward the surface of the work to be dried and having spacings between them for the escape of gas which has acted upon such work, the ratio of the total orifice area to the total area of the work exposed to said jets being between two and four percent, the distance between said nozzles approximating one inch between centers and the distance from the nozzles to said surface being not more than three-eights of an inch.

5. In a dryer, the combination with a hood and means providing a plenum chamber within the hood, of a plurality of nozzles opening from the plenum chamber toward the surface of the work to be dried at a spacing not to exceed three-fourths of an inch from such work and mutually spaced from each other at a spacing not to exceed approximately two inches to provide inter-nozzle passages communicating with the hood externally of the plenum chamber, means for supplying a drying gas under pressure to said chamber for delivery at high velocity from said nozzles, the width of each such nozzle being less than the spacing between the nozzle and the work, whereby the velocity of gas impingement on the work exceeds the velocity of gas movement along the work, and a circulatory system of which said means constitutes a part, said system including a return conduit from said hood and a supply conduit to said plenum chamber, the plenum chamber having a wall opposite the work to be dried which comprises a series of channels having base portions connected to the plenum chamber, said channels having opposing flanges, means connecting the flange of one channel to the flange of the next at the ends of said flanges to constitute said nozzles between successive flanges, the space within the channels constituting said return passages accommodating flow of gases from the work to the hood, the side margins of the channel flanges being mutually divergent whereby the opposing walls constituting respective nozzles are convergent at the tips of said nozzles, the nozzle openings being greatly elongated as compared with their said width and being spaced from each other between three-fourths inch and two inches, center to center, the ratio of total nozzle opening to total work area being in the approximate range of 1.5 percent to 5.5 percent.

6. The device of claim 5 in which the ends of respective channels extend beyond the plenum chamber, the said means connecting the ends of the channel flanges being disposed externally of the plenum chamber and the base portions of respective channels being relieved externally of the plenum chamber, whereby the interior portions of respective channels are opened into the hood.

7. In a web dryer of the type in which the work to be dried is exposed to jets of drying gas, the combination with means for advancing along a predetermined path the work to be dried of a plurality of jets elongated transversely of said path and continuous for substantially the full width of the work, said jets being very narrow in the direction of the work and directed toward the surface of the work to be dried and originating at a distance of not more than three-fourths of an inch therefrom and at a spacing of not less than three-fourths inch and not more than two inches from each other, the ratio of the total cross sectional area of the jets at their origin to the total exposed work area being no less than one and one-half percent and no more than five and one-half percent.

8. In a web dryer of the type in which the work to be dried is exposed to jets of drying gas, the combination with means for advancing the work to be dried along a predetermined path of means immediately adjacent said path for establishing a plurality of jets directed toward the surface of the work to be dried, said means comprising nozzle slots elongated transversely of the direction of advance of the work to be dried and continuous for substantially the width of such work and being at a distance of not more than three-fourths of an inch from the work surface and constituting means for spacing the jets not less than three-fourths of an inch and not more than two inches from each other and for giving them a total area at said means of not less than one and one-half percent or more than five and one-half percent of the total exposed work area.

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# UNITED STATES PATENT OFFICE
# CERTIFICATE OF CORRECTION

Patent No. 3,176,412 April 6, 196[illegible]

Thomas A. Gardner

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 10, lines 11 to 13, the formula should appear as shown below instead of as in the patent:

$$h_m = n\left(\frac{V}{L}\right)^{1/2}$$

same column 10, lines 33 to 37, the formula should appear as shown below instead of as in the patent:

$$\frac{V}{\bar{V}} = \left(\frac{D}{\alpha Y + \frac{D}{2}}\right)^{1/2}$$

same column 10, line 42, for "δ" read -- α --.

Signed and sealed this 28th day of September 1965.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents