SOME CONSIDERATIONS OF THE FLOW OF AIR IN TIMBER SEASONING KILNS.

Thesis submitted for examination for the degree of Master of Engineering

By - W.L. Greenhill.

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SUMMARY.

The present investigations have been initiated with the object of studying the air circulation and relation between the air movement and the drying of the timber in timber seasoning kilns. The work has been divided into five separate experiments, each of which is summarised separately as follows :-

Experiment 1 - The Measurement of the Flow of Air Through Timber Stacks. - A method of measuring the air velocity through timber stacks by means of vane anemometers has been established. Correction factors, which, for any one size and type of anemometer depend on the thickness of the timber and of the separating strips, on the velocity, and on the position in which the anemometer is held, have been determined for a number of cases. These have been plotted against recorded anemometer readings on a number of graphs.

Experiment 2 - The Effect of the Rate of Air Circulation on the rate of Drying. - A number of kiln runs has been made with narrow stacks of matched material using the same temperature and humidity in each run but different rates of air circulation. The object has been to determine the effect of the rate of air circulation on the rate of drying timber apart from the question of change of drying rate from one side of a wide stack to the other due to fall in temperature and increase in humidity of the air. The results indicate that with the same air conditions the rate of drying is independent of the rate of air flow provided that this rate is greater than some minimum value which is probably in most cases less than 140 feet per minute.

Experiment 3 - The Relation Between the Quantity of Air Circulated and the Lag in Drying From the Entering to the Leaving Air Side of a Kiln Charge of Timber. - A number of tests has been carried out in an experimental kiln to determine the change in air conditions and the lag in the drying rate from the entering to the leaving air side of a stack of timber 5 feet wide. Different sized separating strips and different quantities of circulating air have been used. The theoretical relation between the quantity of air circulated, the amount of moisture evaporated, and the change in air conditions has also been established; the results so calculated have been compared with those determined experimentally.

Experiment 4 - The Relation Between Air Flow and Fall in Pressure Across a Timber Stack. - The flow of air through a rectangular duct consisting of boards and separating strips and similar to the openings through a timber stack has been investigated. Curves showing the relation between static pressure change and rate of flow have been prepared for different sized strips and for board surfaces of different degrees of roughness. Equations for the pressure loss during flow through the duct and for the entrance pressure loss have been determined.

Experiment 5 - The Effect of Various Features of Kiln Design on the distribution of the Air over the Side of a Stack of Timber in a Commercial Kiln. - A series of tests has been carried out in commercial kilns of the cross shaft internal fan type to determine the effect of various distances between the kiln walls and the sides of the stack on the distribution of the circulating air over the side of the stack. The results of the tests are shown diagrammatically. The conclusion is reached that the 16 inch wide space commonly adopted for the particular design of kiln tested is reasonably satisfactory although more comprehensive tests on an experimental kiln of commercial proportions appear desirable.

INTRODUCTION.

The increasing importance being attached to the kiln seasoning of timber has served to emphasise the need for more definite information with regard to the question of air circulation in kilns, In the past many factors relating to the design of forced circulation kilns, which are now recognised to be by far the most satisfactory for the great majority of purposes, have been contributed as a matter of guesswork. The object of the present work has been to investigate the quantity of air required for the drying of timber and the factors affecting its delivery and distribution through a stack of timber.

It is recognised that the work which has been completed so far and which is described in this thesis falls far short of a complete investigation of the problems involved. Actually a number of new fields of investigation have suggested themselves as a result of the present work. On the other hand, however, much useful information has been obtained which it is hoped will at least form a basis ~~on which to base~~ for further work.

The investigation has been divided up into a number of more or less independent experiments as follows :-

1. The measurement of the flow of air through timber seasoning stacks.

2. The effect of rate of air circulation on rate of drying.

3. The relation between the quantity of air circulated and the lag in drying from the entering to the leaving air side of a kiln charge of timber.

4. The relation between air flow and fall in pressure across a timber stack.

5. The effect of various features of kiln design on the distribution of the air over the side of a stack of timber in a commercial kiln.

Details of each experiment and its relation to the problem of kiln design have been set out separately in the following pages.

EXPERIMENT 1.

THE MEASUREMENT OF THE FLOW OF AIR THROUGH TIMBER STACKS.

INTRODUCTION.

These investigations are concerned largely with the quantity and distribution of the air circulated through stacks of timber in seasoning kilns and for this reason the first essential part of the work was to establish a simple and accurate method of measuring this air flow. Furthermore, it was evident that, for tests at commercial plants, apparatus which was readily portable and easily brought into use without interfering with the normal operations of the plant was very desirable.

Of the various established methods of measuring air-flow which are well described by Ower (1), only two appeared to warrant consideration, namely, those involving the use of the Pitot tube and vane anemometer respectively. On account of the comparatively low velocities encountered in practice the use of the Pitot tube would have necessitated the use of a manometer much more accurate than the usual type of portable instrument and such sensitive instruments are practical for use only in laboratories. There seemed little doubt that the best type of instrument for such air flow measurements as would need to be made in the course of the work was the vane anemometer, and the problem resolved itself into one of how to use this instrument and how properly to interpret its indications.

As far as can be determined measurements of the air flow through timber stacks have, in the past, been made either by:

1. Measuring the time required for a whisp of smoke to move from one side of a stack to the other, or,

2. By using an anemometer without any consideration of the possible accuracy of readings on an instrument of this type under such conditions, or,

3. By measuring the total air delivered to the side of a stack and from the dimensions of the openings through the stack calculating the average flow through each opening.

Of these three methods the last only can have any claim to accuracy. Such a method is, however, of no value where the velocity distribution over the side of the stack is to be investigated. In the first method mentioned, the velocity determined is probably more nearly the maximum than the average through the opening; in the second method the readings obtained depend to a large extent on a number of factors such as the position in which the anemometer is held relative to the rows of boards and openings between them. It is with the determination of these factors which affect the anemometer readings that the present experiment is concerned.

APPARATUS.

The apparatus used ~~in~~ the tests is shown in Figure 1.

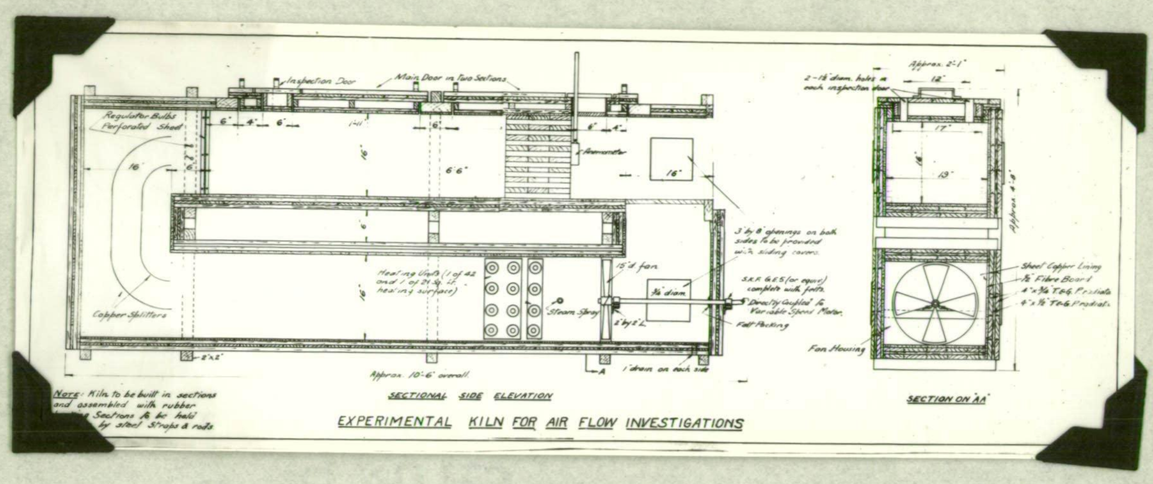


FIG.1. Arrangement of kiln for air flow measurements.

It consists of a special kiln fitted with a propellor type fan directly coupled to a variable speed motor. Air passes in to the fan through the side inlets and is delivered through the metal splitters to the top chamber. A perforated metal plate at the entrance to this helps to even out the air distribution in the chamber. Large doors fitted with small inspection doors provide access to the top chamber in which the timber stacks were constructed. After passing through the stacks of timber the air passes directly out through the end of the chamber into the room.

Two anemometers were used in the tests and these are shown in Figure 2. The first one is an ordinary Biram type

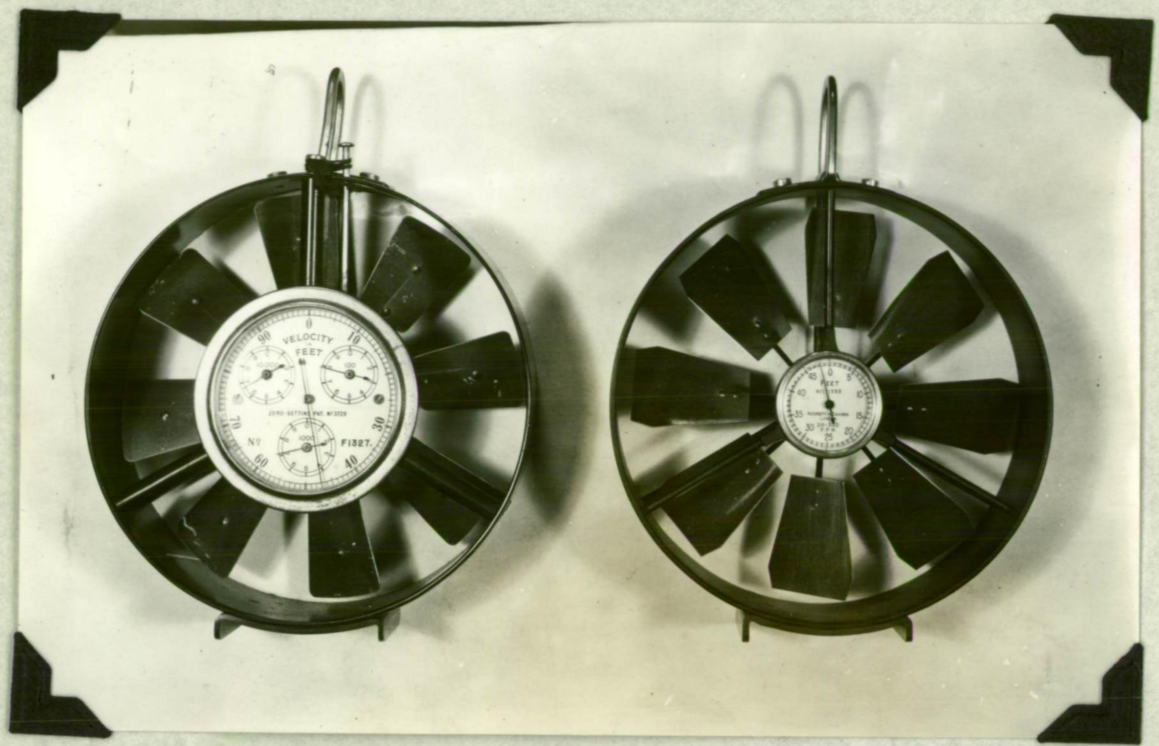


FIG.2. Ordinary Anemometer (left) and Low Speed Anemometer. instrument, 4-in. in diameter, and designed to measure air speeds from 100 to 3,000 feet per minute. The second anemometer is of the same general design, 4-in. in diameter, but specially constructed to measure low air speeds from 30 to 500 feet per minute. The latter instrument was obtained specifically for this work and carried with it the manufacturer's (Messrs. Negretti & Zambra, London) certified calibration. The first anemometer was carefully calibrated against the low speed instrument for speeds up to 500 feet per minute before the actual tests were commenced.

MATERIAL USED.

Material was prepared for building timber stacks in the kiln 12-in. long in the direction of air flow and of any of the following thicknesses: $\frac{1}{4}$-in. $\frac{1}{2}$-in. $\frac{3}{4}$-in. 1-in. $1\frac{1}{2}$-in. and 2-in. The actual timber used was Mountain ash (Eucalyptus regnans) which was carefully sawn to size but was not planed. Separating strips $\frac{3}{8}$-in. $\frac{1}{2}$-in. $\frac{5}{8}$-in. $\frac{3}{4}$-in. $\frac{7}{8}$-in. 1-in. $1\frac{1}{4}$-in. and $1\frac{1}{2}$-in. thick were used.

PROCEDURE.

Each stack was built in the position shown in Figure 1, that is, with the leaving air side just below the second small inspection door opening. Provision was made for lowering an anemometer through this opening by means of a thin steel rod and while readings were being taken to seal round the rod. Similar provision was made at the first small inspection door opening. In the latter position the free cross section of the chamber was assumed divided into sixteen equal rectangles and at the centre of each of these, anemometer readings were taken of the air velocity. Observations were made from the open end of the chamber by focussing an electric torch through suitable openings in the timber stack on to the anemometer. The average of the sixteen readings multiplied by the free area of the chamber was taken to be the actual air flow and from this and the measured area of the openings through the timber stack the average velocity through the stack could be readily calculated.

When the anemometer was held against the timber stack, that is, through the second inspection door opening, its reading was affected by the timber which, of course, interrupted the flow of air to the vanes. Furthermore, the effect of the timber on the instrument readings was different for different positions of the anemometer relative to the openings. It was decided to determine the readings with the anemometer in two easily specified positions, namely :

(a) With the centre of the anemometer over the centre of an opening, and,

(b) With the centre of the anemometer over the centre of a layer of timber.

In each case sixteen readings were again taken, the positions of the anemometer as closely as possible corresponding to the positions in the open chamber. These tests were made with both the ordinary and low speed anemometer except in those cases where the air speed was outside the range of the instrument. The air speed through the open chamber was measured in each case with the low speed anemometer. With each different stack velocities were measured at five different fan speeds.

From the actual average velocity through the stack, calculated from the anemometer readings in the open chamber, and the average of the readings obtained from the anemometer against the stack on the leaving air side, correction figures were obtained by which the latter readings must be multiplied to give the correct average air velocity.

RESULTS.

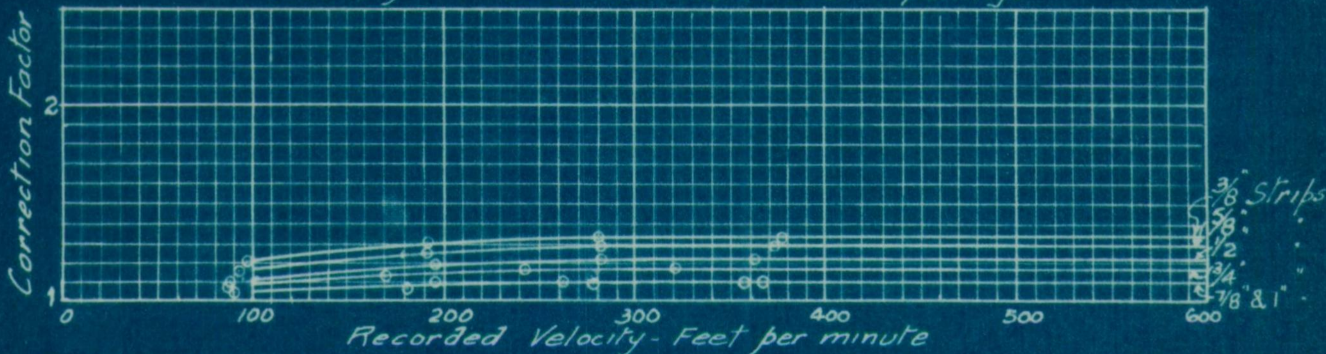
The results of these tests are shown in graphical form on the following blue prints. Each of the six sheets deals with a different size of timber and on each is plotted for each size of strip the correction factor against the recorded velocity for the two different anemometers and for the two positions of the anemometers relative to the openings through the stack.

In connection with these tests it is of interest to note that the air distribution in the upper chamber of the kiln was exceptionally uniform except at very low velocities when the rate of air movement at the bottom of the chamber was somewhat slower than at the top. This lack of uniformity became really apparent only at air velocities less than 100 feet per minute.

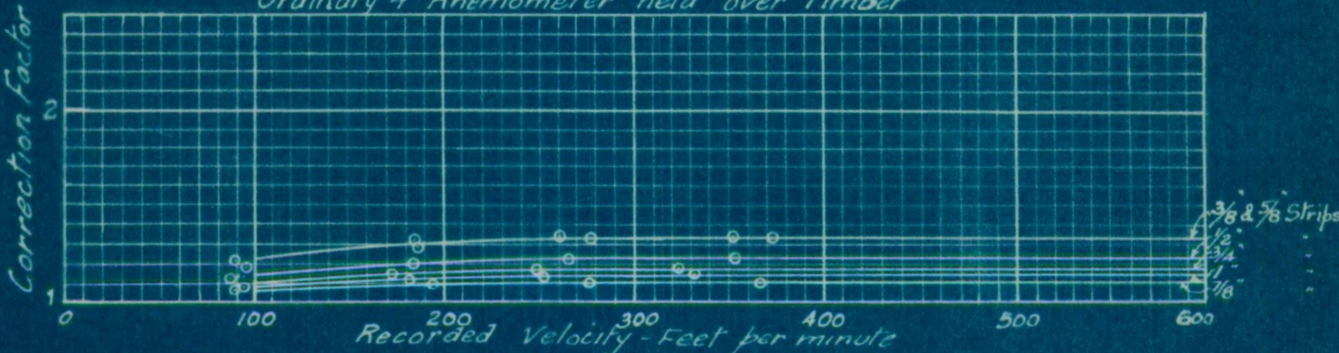
DISCUSSION OF RESULTS.

It will be seen that all the curves tend to become horizontal as the velocity is increased; when this condition is reached the correction factor is apparently independent of further increase in velocity.

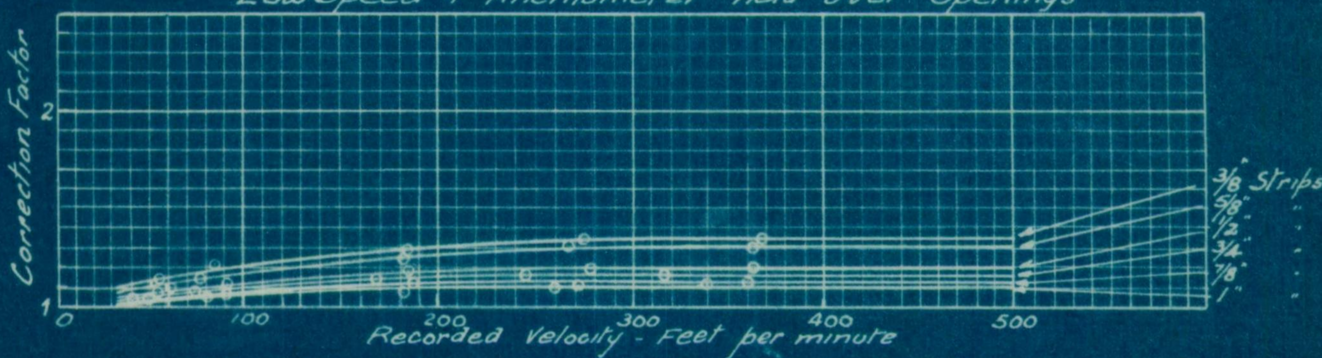
Ordinary 4" Anemometer held over Openings



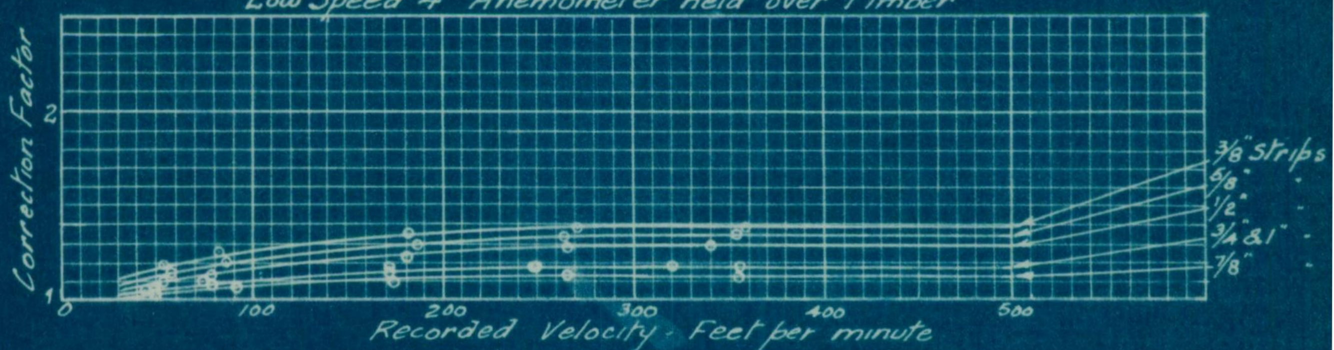
Ordinary 4" Anemometer held over Timber



Low Speed 4" Anemometer held over Openings

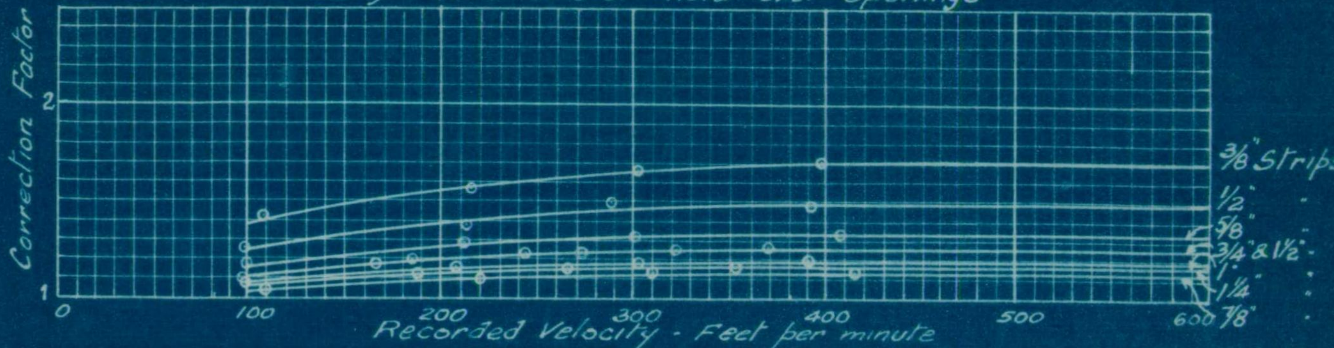


Low Speed 4" Anemometer held over Timber

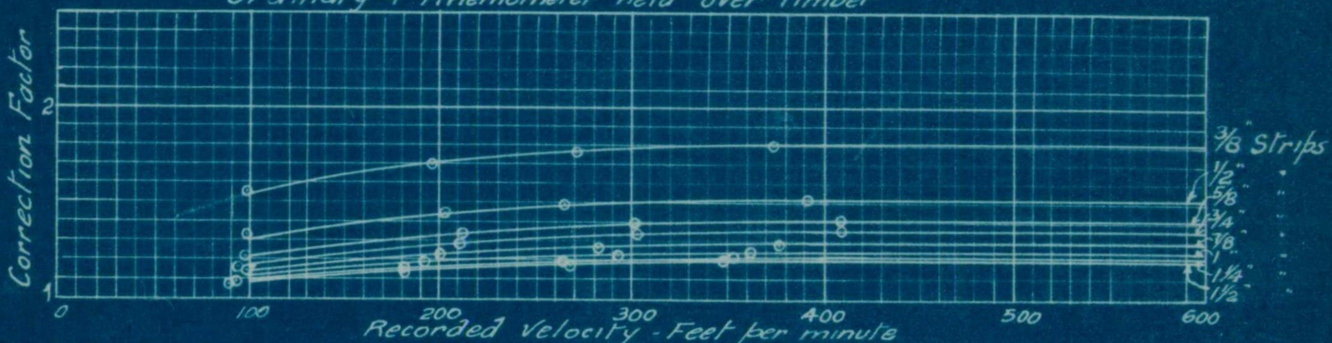


CORRECTION FACTORS TO BE APPLIED WHEN MEASURING THE AIR FLOW THROUGH STACKS OF 1/4-INCH TIMBER

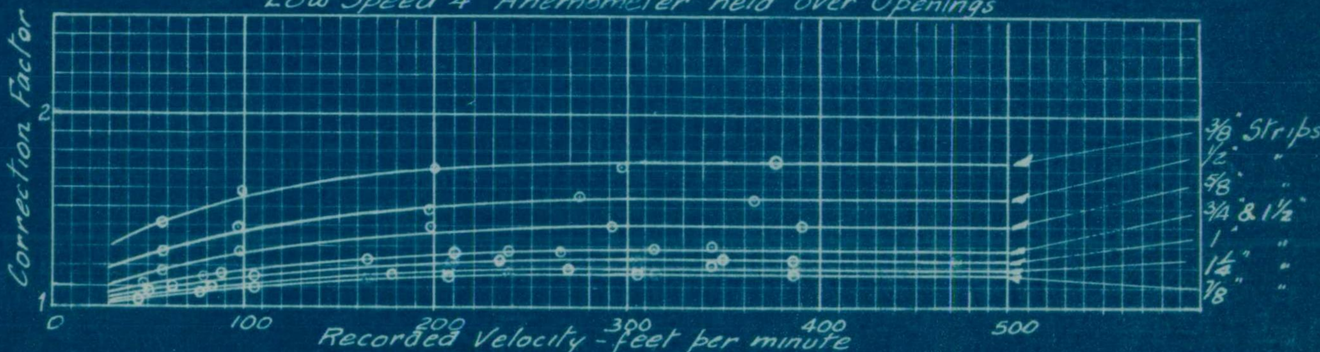
Ordinary 4" Anemometer held over Openings



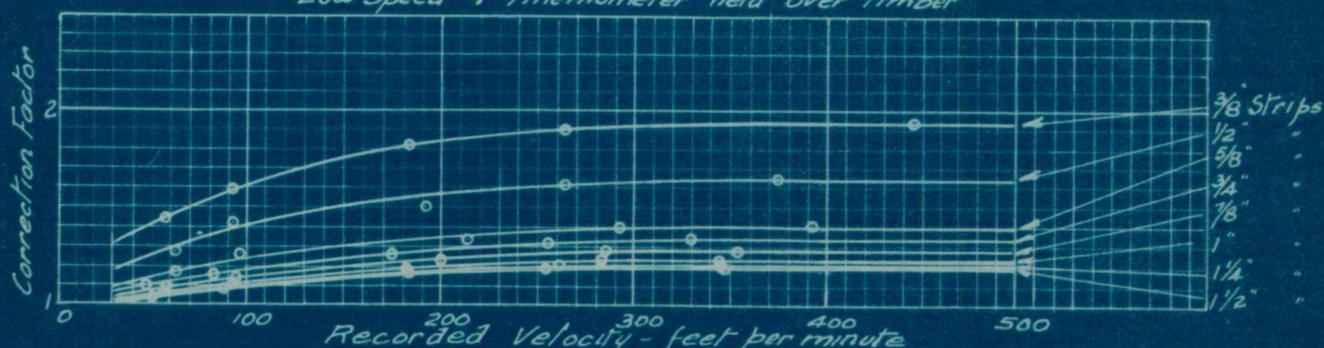
Ordinary 4" Anemometer held over Timber



Low Speed 4" Anemometer held over Openings

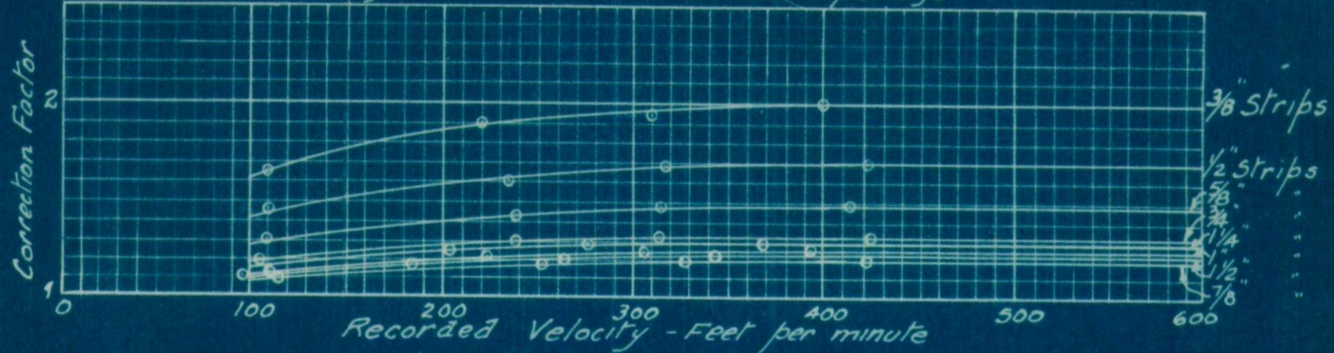


Low Speed 4" Anemometer held over Timber

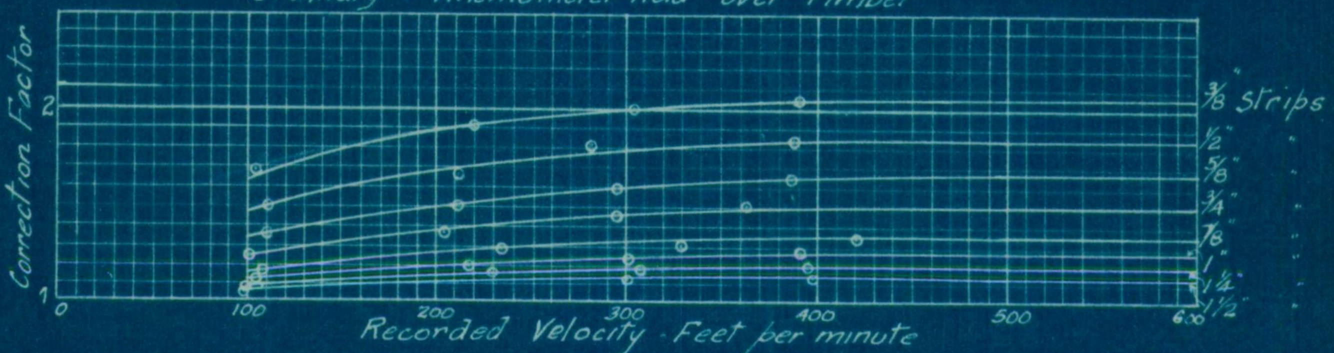


CORRECTION FACTORS TO BE APPLIED WHEN MEASURING THE AIR FLOW THROUGH STACKS OF 1/2-INCH TIMBER

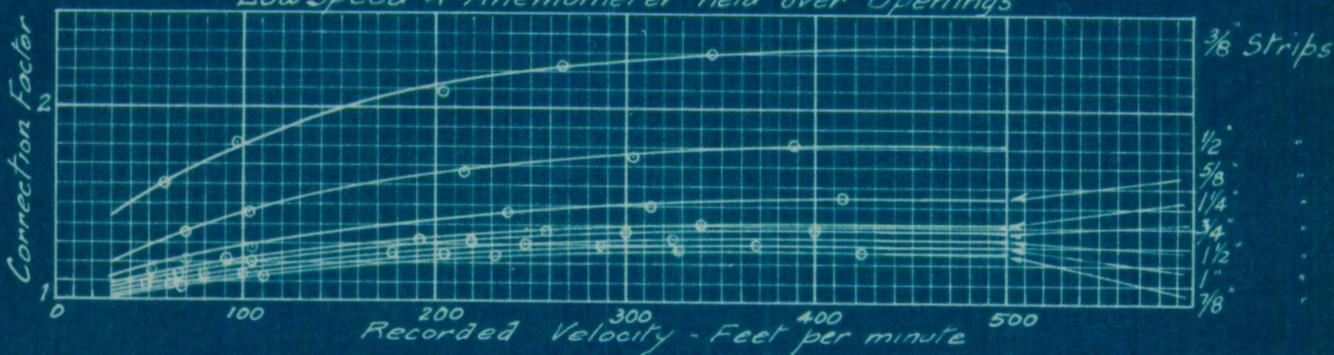
Ordinary 4" Anemometer held over Openings



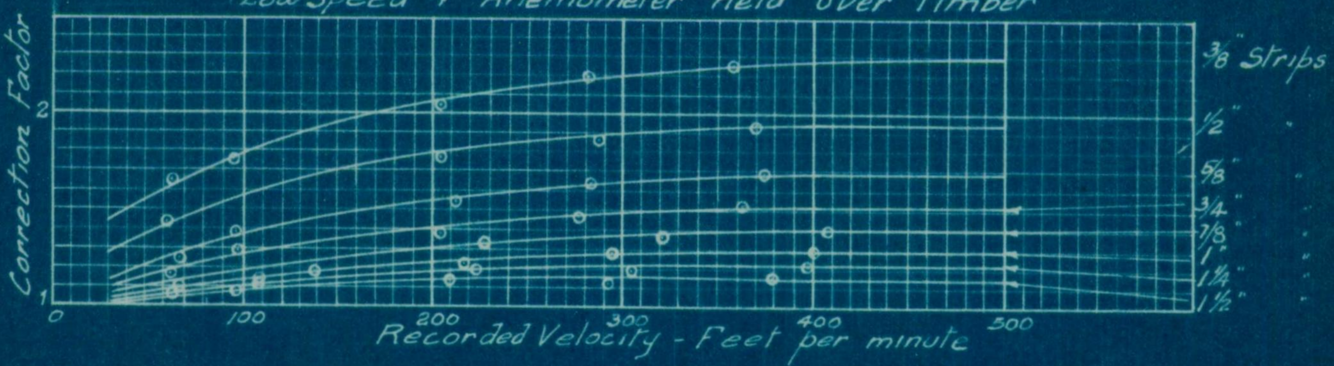
Ordinary 4" Anemometer held over Timber



Low Speed 4" Anemometer held over Openings



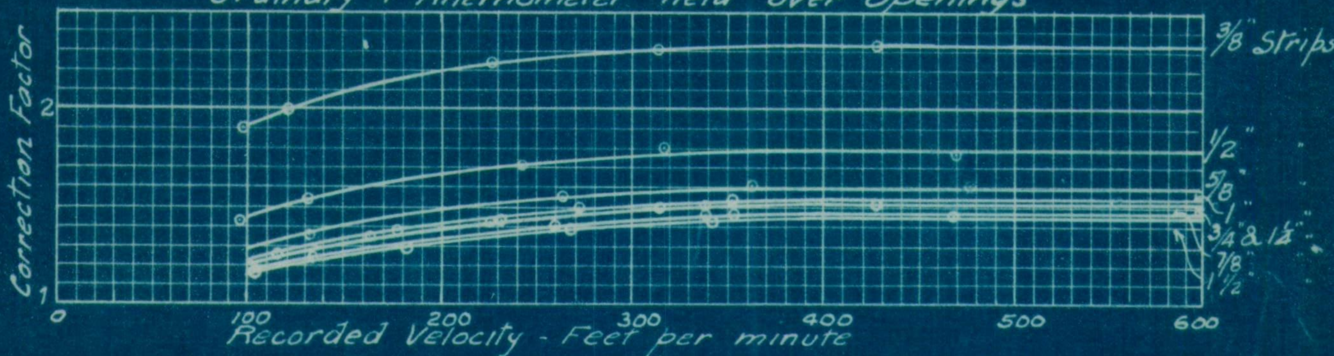
Low Speed 4" Anemometer held over Timber



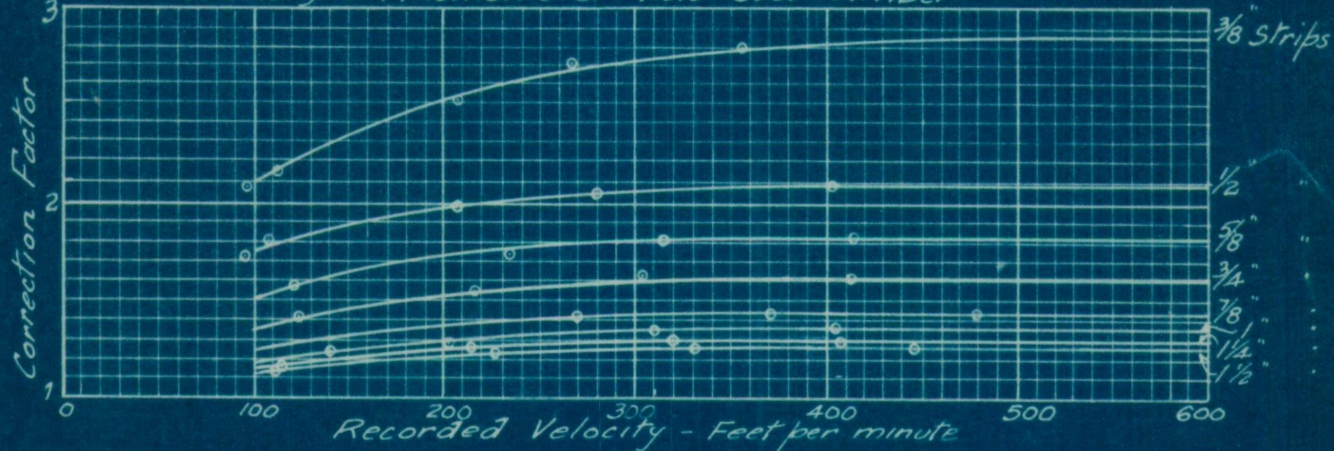
CORRECTION FACTORS TO BE APPLIED WHEN MEASURING

THE AIR FLOW THROUGH STACKS OF 3/4-INCH TIMBER

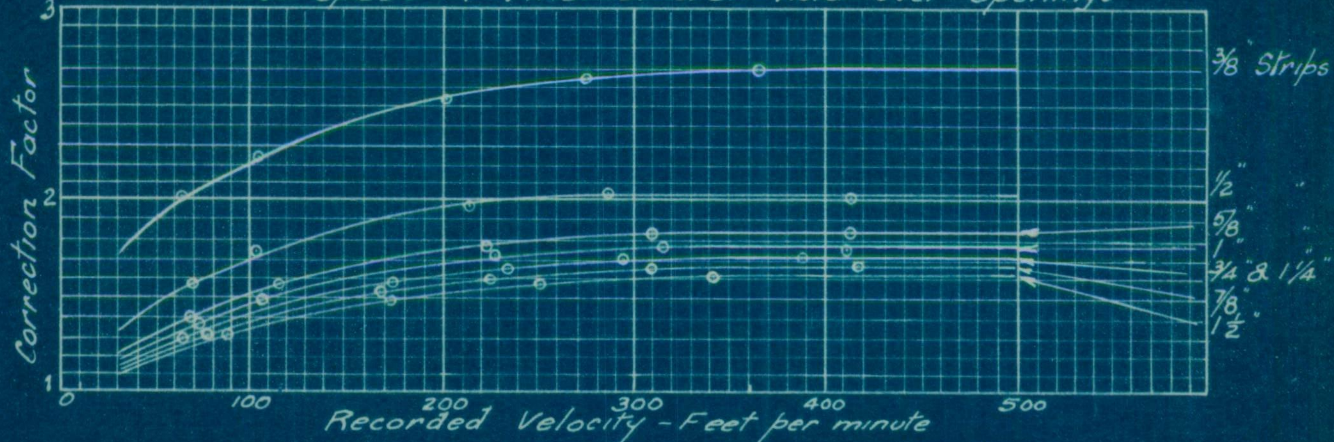
Ordinary 4" Anemometer held over Openings



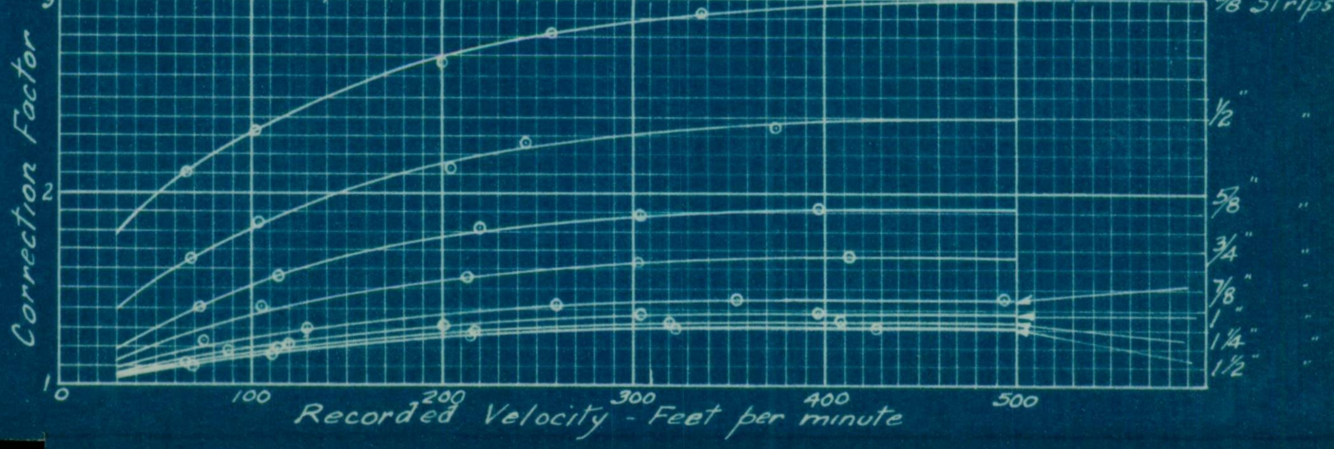
Ordinary 4" Anemometer held over Timber



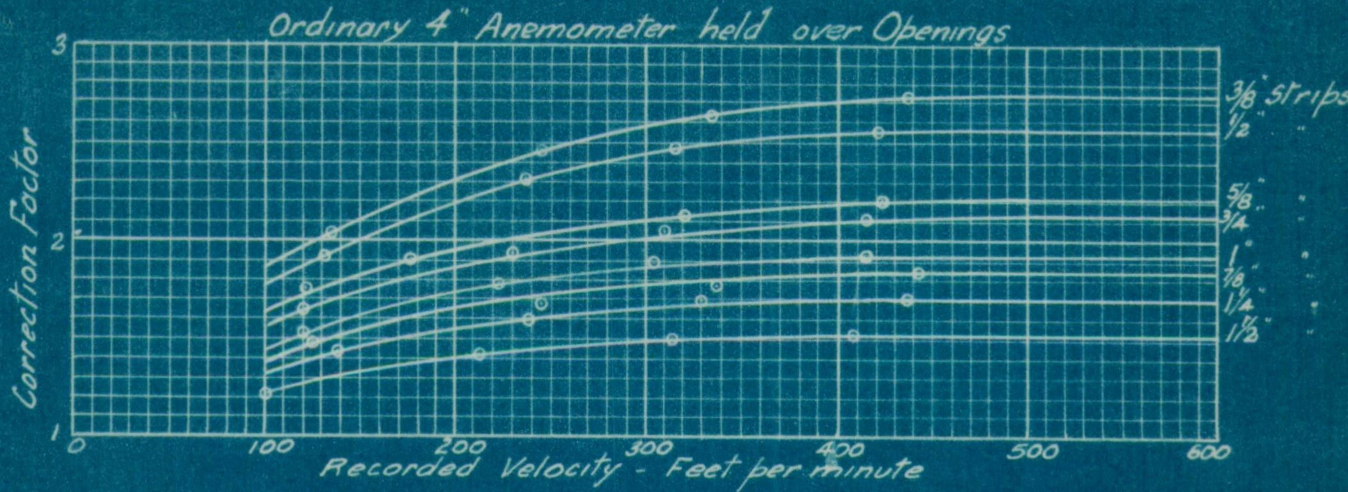
Low Speed 4" Anemometer held over Openings

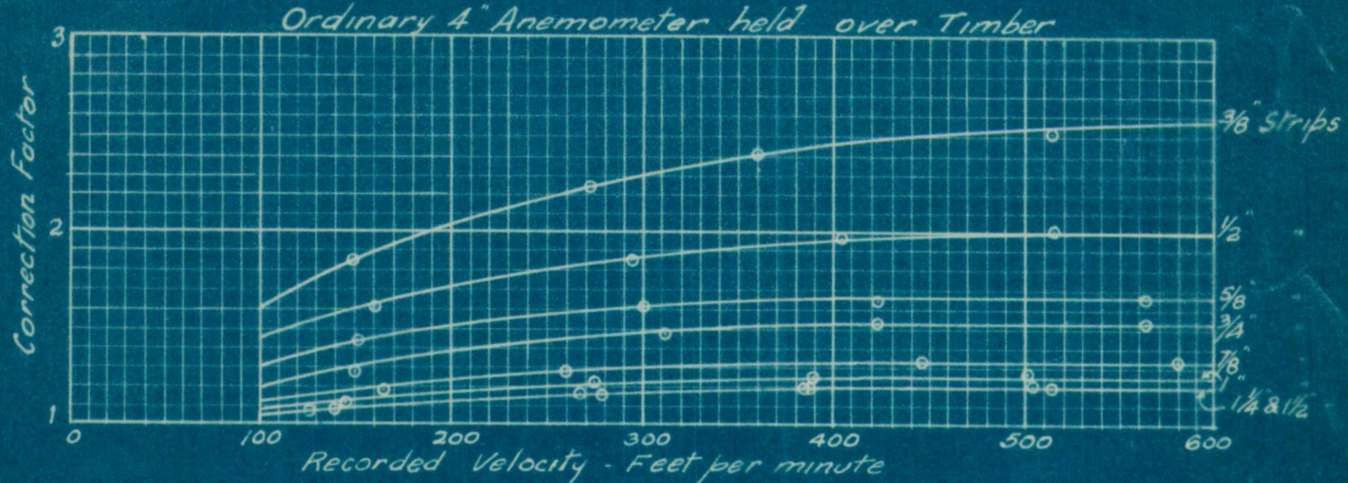


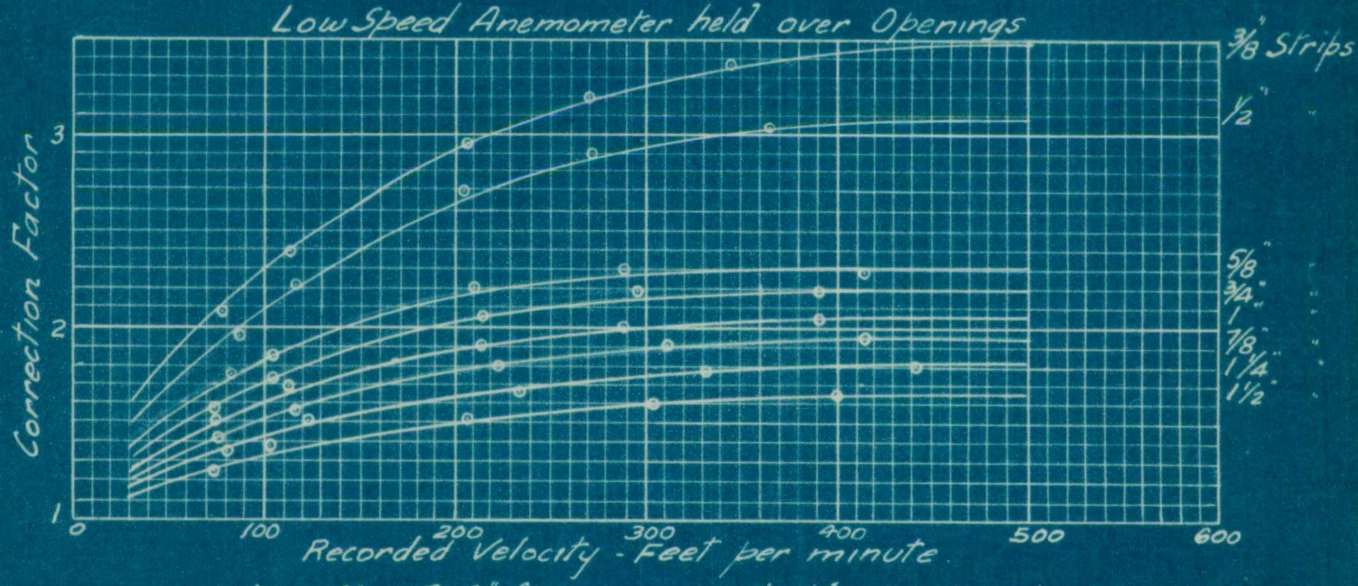
Low Speed 4" Anemometer held over Timber

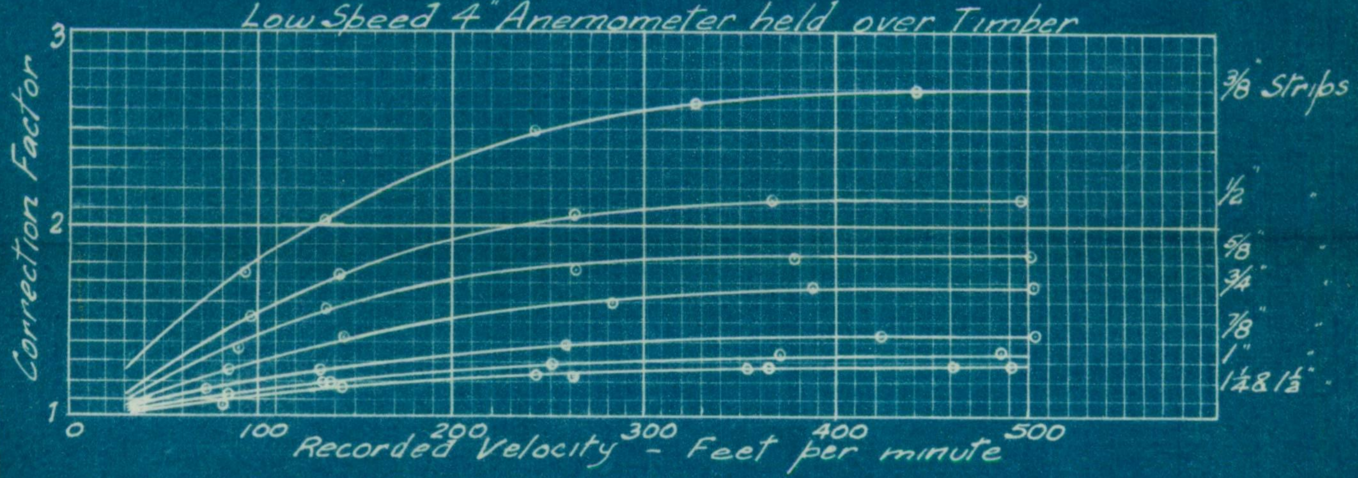


CORRECTION FACTORS TO BE APPLIED WHEN MEASURING THE AIR VELOCITY THROUGH STACKS OF 1-INCH TIMBER.

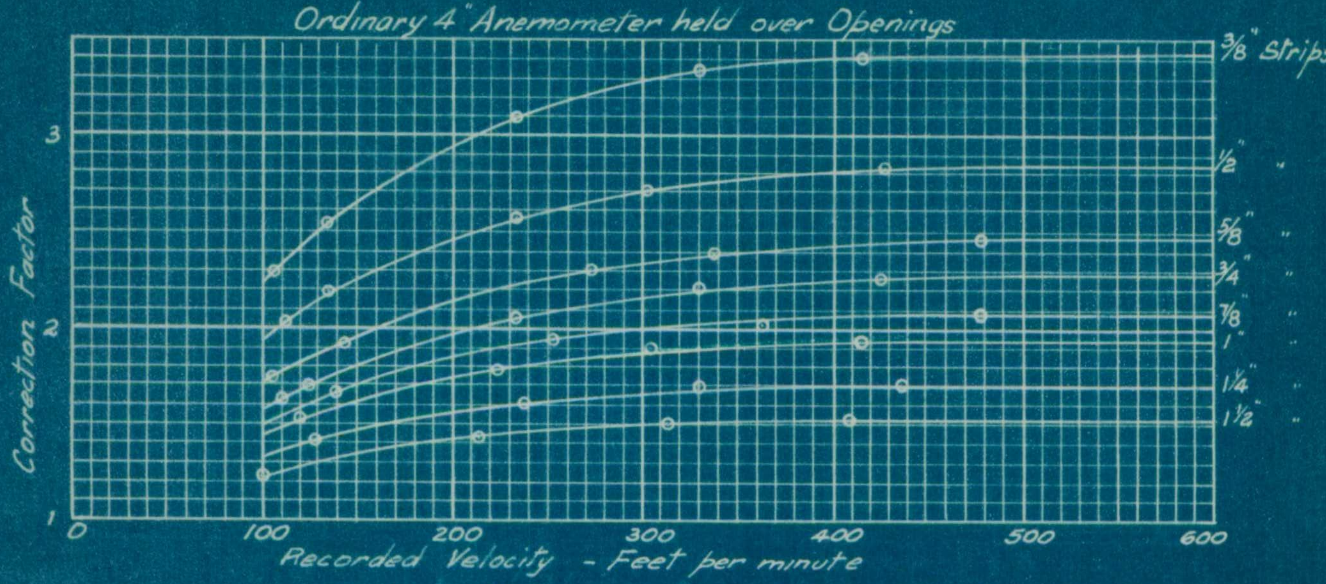


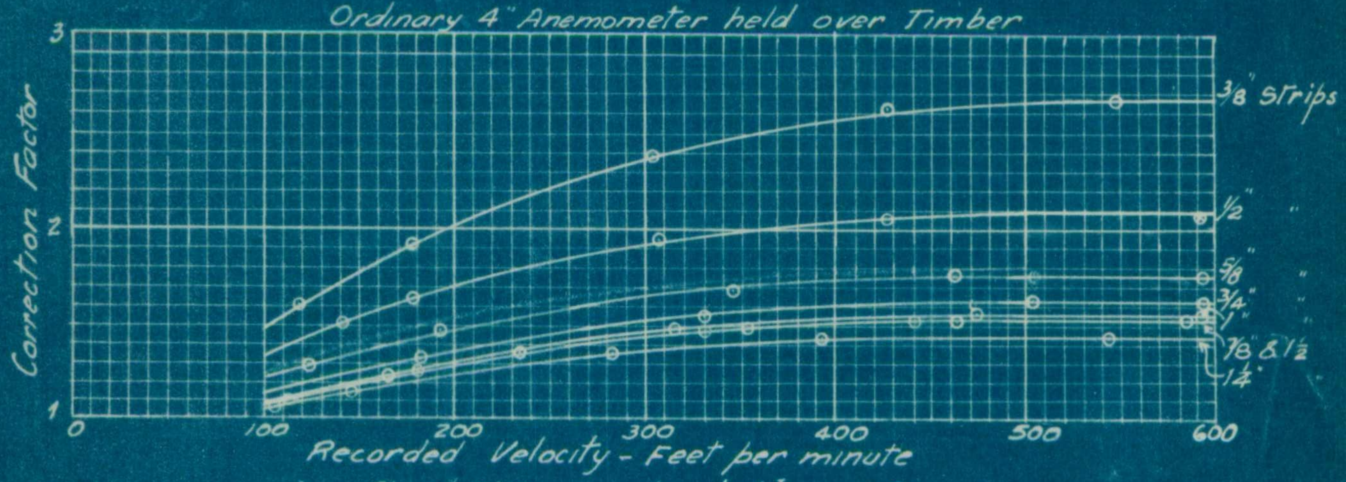


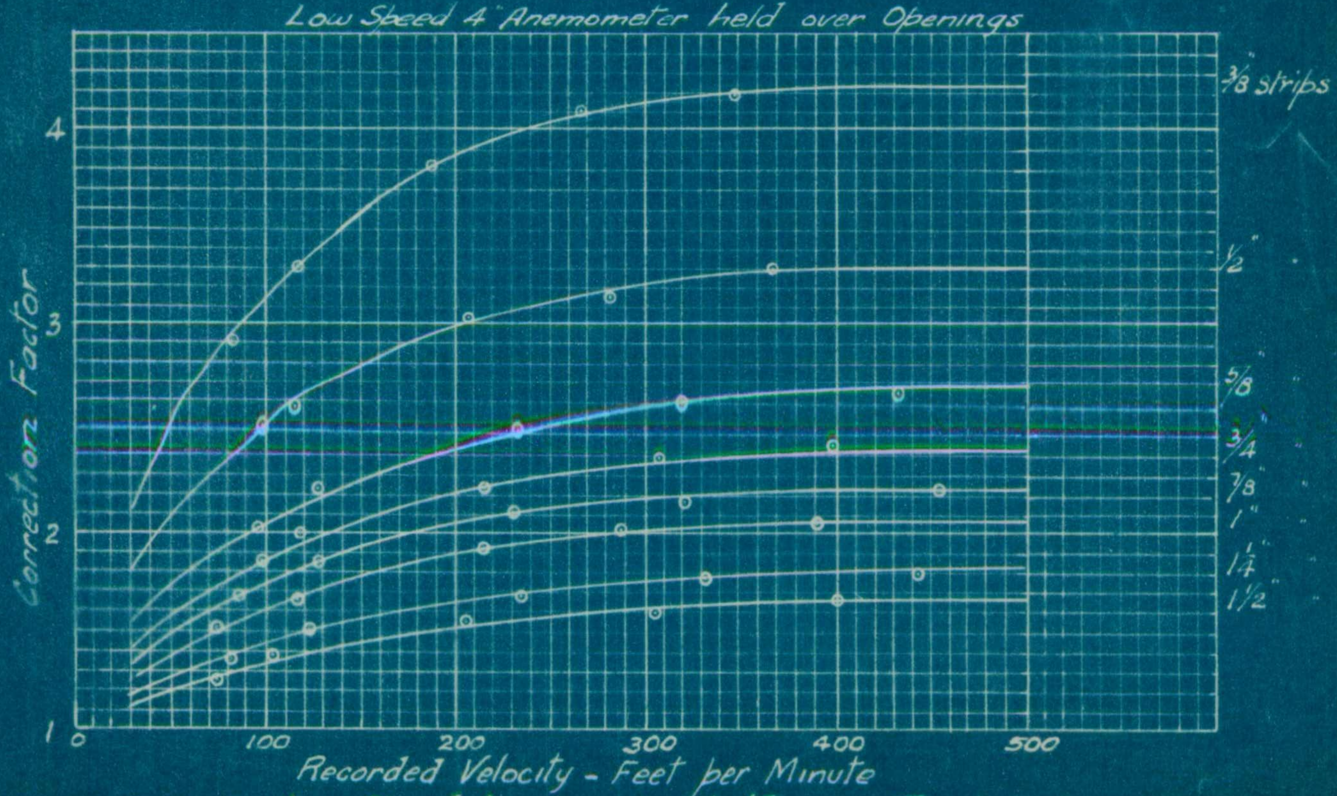


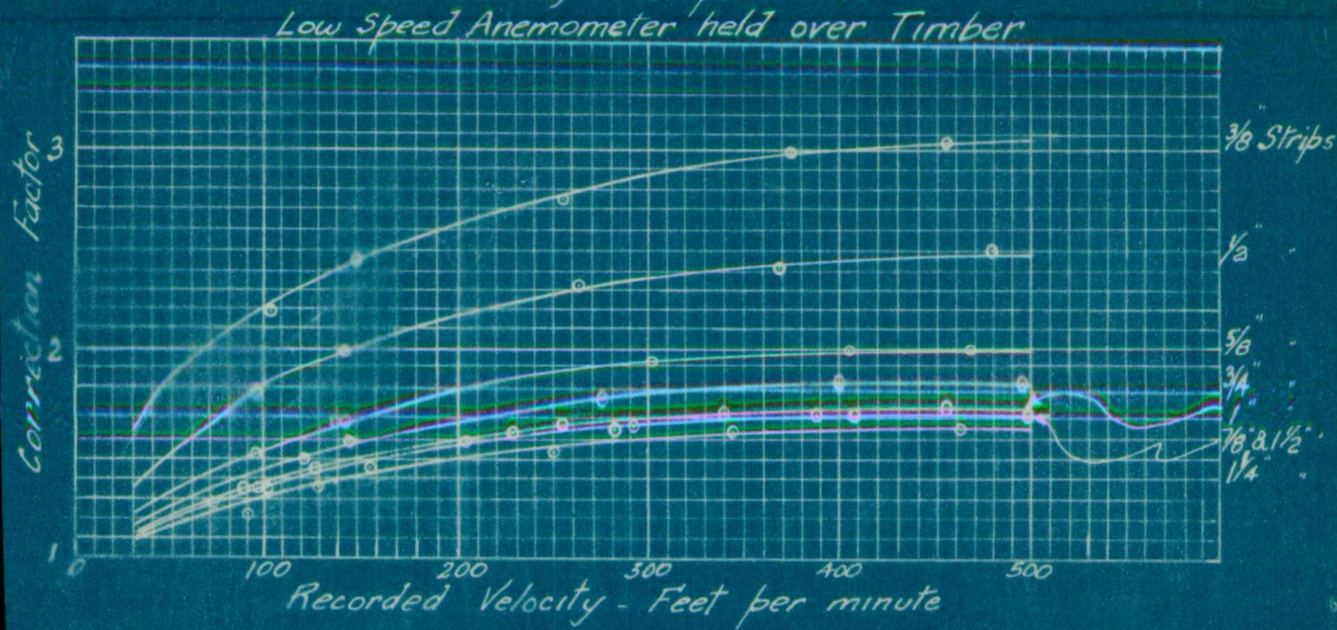


CORRECTION FACTORS TO BE APPLIED WHEN MEASURING THE AIR VELOCITY THROUGH STACKS OF 1½-INCH TIMBER









CORRECTION FACTORS TO BE APPLIED WHEN MEASURING THE AIR VELOCITY THROUGH STACKS OF 2-INCH TIMBER

There is an appreciable difference between the co-efficients obtained for the two anemometers except perhaps with the thinner timber. The curves for the low speed anemometer are drawn from recorded velocities of 30 feet per minute to 500 feet per minute, those for the ordinary anemometer from 100 to 600 feet per minute. These cover the usual range of velocities met in practice in forced circulation kilns.

There is also an appreciable difference between co-efficients obtained with the anemometers in the two positions relative to the openings through the stacks, although neither position seems to have any distinct advantage over the other. For timber thicker than 2-in., the co-efficients for the 2-in. timber with the instruments over the openings can be used as in this case only one opening affects the anemometer. For the ¼-in. timber separating strips larger than one inch have not been considered. It will be noted that in some cases the curves for the different sized strips are not in the order of the sizes. The reason for this is apparent when the actual openings discharging air to the vanes of the instrument are considered.

In practically all commercial kilns the air after leaving the stack must be turned at right angles as it returns to the fans. The possibility that the direction of the air has been changed before it passes through the anemometer has been considered. Smoke tests indicate, however, that the direction is not changed sufficiently in the short length to seriously affect the results, and later tests (see Experiment 5) confirm this opinion. Ower (1) has shown that a wind angle as great as 20^{o} affects the anemometer reading by less than 1 per cent.

EXPERIMENT 2.

THE EFFECT OF RATE OF AIR CIRCULATION ON RATE OF DRYING.

INTRODUCTION.

Evidence as to the effect of rate of air circulation on the rate of drying of timber, apart from the question of change in drying rate from one side of a wide stack to the other due to fall in temperature and increase in humidity of the circulating air, is somewhat conflicting. Unpublished results of work at the Forest Products Laboratory, Madison, U.S.A.[x] appear to indicate that the rate of drying can be increased by increasing the velocity of air circulation up to velocities of the order of 2000 feet per minute, although the increase in drying rate becomes progressively less as the velocity is increased. The explanation suggested for this behaviour is as follows: in order for the timber to dry, moisture must move from within to the surface and then be carried away by the circulating air. Just whether the moisture moves through the timber as water or vapour, that is, whether the "driving force" is due to the moisture gradient or to a difference in vapour pressure, is rather obscure, but does not affect this explanation. The resistance to the movement of the moisture and its removal

[x]Conveyed to the author during personal interviews.

by the circulating air consists of two parts, one of which depends on the structure of the timber, while the other is a "surface" resistance. Provided there is sufficient air to convey the heat necessary to evaporate the moisture and separate it from the wood as fast as it reaches the surface and then carry away this evaporated moisture, any further increase in volume of the circulating air can affect the drying only by reducing the so-called surface resistance. It is suggested, that the greater the air velocity, at least up to certain limits, the less is this surface resistance, and the faster the rate of drying of the timber.

On the other hand Jenkins (2) has carried out a number of experimental kiln runs which indicate that the rate of drying of Douglas fir is independent of the air velocity over a range of velocities from 120 to 330 feet per minute.

In order to obtain further information relative to the effect of rate of air circulation the tests described in the present report have been carried out.

MATERIAL USED.

Species.

Blackwood	...	(*Acacia melanoxylon*)
Karri	...	(*Eucalyptus diversicolor*)
Kauri	...	(*Agathis australis*)
Matai	...	(*Podocarpus spicatus*)
Rimu - sap	...	(*Dacrydium cupressinum*)
Silver beech	...	(*Nothofagus menziesii*)

Tawa	...	(*Beilschmiedia tawa*)
Totara	...	(*Podocarpus totara*)
White pine	...	(*Podocarpus dacrydioides*)

Preparation.

Four quartersawn boards 4-in. by ¾-in. by 18-in. long were sawn from each of two different flitches of each of the above species. The total number of boards was thus 72. These were divided into four groups of matched boards for four kiln runs, each group containing one board from each flitch.

PROCEDURE.

In all four kiln runs the boards were stacked in the kiln in the same position. The stack was two boards wide (8-in) in the direction of air flow and the two boards side by side were of the same species. Two cover boards in addition to the test boards completed the charge. Three-quarter inch separating strips were used. The stacks were located with the leaving air side immediately beneath a small inspection door to facilitate the insertion of the anemometer for measuring the air velocity.

In the four runs the same wet and dry bulb temperatures were maintained (110°F. and 120°F.) but different air velocities were used in different runs, variation being provided by varying the fan speed and baffling the fan intake.

The air velocities were measured by the method described in Experiment 1, the anemometer in these tests being fitted with a small mirror in front of the dial to facilitate its being seen from immediately above. Corrections were made for the temperature of the air.(see Ower (1)).

The boards were weighed daily. At the completion of each run moisture content sections were cut from all boards. Drying curves were prepared and from the curves the drying rates determined.

RESULTS.

For comparative purposes the results have been set out in the following table (page 18) which gives the air velocities and the corresponding drying rates for various stages of the drying. The boards of any one species were all at about the same initial moisture content but this varied considerably in different species.

The two lower velocity figures must be taken as approximations only, especially the smaller of these as at this velocity the anemometer only just moved. Furthermore, at these low velocities the air distribution across the chamber is far from uniform. However, the figures are thought to be fairly close to the average velocities of the air through the stacks in the respective runs.

DISCUSSION OF RESULTS.

Perhaps the most important point indicated by this

TABLE GIVING AIR VELOCITIES AND DRYING RATES.

Species	Air Velocity, ft/min.	Rate of Drying (grams of moisture per hour) during drying from 110% to 100%	100% to 90%	90% to 80%	80% to 70%	70% to 60%	60% to 50%	50% to 40%	40% to 30%	30% to 20%
Blackwood	292			11.7	7.8	6.0	4.1	3.1	2.0	-
	140			11.6	7.7	5.9	4.1	3.1	2.0	-
	30			3.5	3.5	3.5	3.3	3.2	-	-
	15			2.2	2.1	2.1	-	-	-	-
Karri	292							4.1	1.7	
	140							4.2	1.6	
	30							3.2	1.5	
	15							2.0	1.5	
Kauri	292								6.7	4.0
	140								6.8	4.0
	30								4.7	2.1
	15								4.2	1.6
Matai	292			19.6	12.8	9.9	6.8	5.2	3.2	1.5
	140			19.8	12.9	9.9	6.9	5.2	3.3	1.5
	30			10.9	8.0	7.0	5.7	5.0	2.9	1.3
	15			5.3	4.6	4.6	3.4	2.3	-	-
Rimu - sap.	292		24.4	20.4	14.3	11.4	10.6	6.9	5.1	3.6
	140		24.3	20.3	14.3	11.3	10.1	6.6	5.0	3.6
	30		5.0	5.4	5.0	5.2	4.9	5.4	4.3	2.9
	15		6.5	6.5	5.0	4.3	-	-	-	-
Silver Beech	292	19.2	13.6	11.3	8.7	7.3	5.4	4.8	3.2	2.5
	140	18.3	13.6	11.2	8.6	7.0	5.3	4.5	3.3	2.5
	30	6.8	6.2	5.8	5.0	4.8	4.3	4.2	3.1	2.4
	15	5.7	4.8	4.8	3.5	-	-	-	-	-
Tawa	292					11.2	7.2	4.7	3.2	2.4
	140					11.7	7.5	5.0	3.3	2.5
	30					8.4	6.7	5.6	3.0	2.4
	15					8.4	6.8	4.8	3.5	2.2
Totara	292		8.8	5.5	3.6	3.2	2.0	1.8		
	140		8.8	5.5	3.6	3.2	1.9	1.7		
	30		4.3	3.7	2.5	2.1	1.9	1.8		
	15		2.0	1.7	1.4	-	-	-		
White Pine	292			27.8	21.2	16.5	11.4	9.5	6.2	3.7
	140			27.8	21.2	16.5	11.4	9.3	6.1	3.8
	30			6.5	5.7	6.1	5.8	5.8	6.1	3.6
	15			5.8	4.9	4.6	3.6	3.7	3.0	-

test is that the drying rate cannot be increased more or less indefinitely by increasing the velocity of the circulating air. Furthermore, the velocity at which the drying rate becomes a maximum appears to be comparatively low - less than 140 feet per minute in every case in the present test, with the possible exception of the silver beech in the first stages of the drying. It is impossible from the limited number of tests made, and with the uncertainty attached to the lower velocity readings to determine the exact magnitude of the velocity above which the rate of drying becomes independent of the velocity. The value may be dependent on the timber and its moisture content.

The rate of drying appears to be influenced by the circulating air in respect to some factor additional to the functions of the air to convey heat to the timber and remove the moisture. If these functions of the air alone influenced the drying rate there would be a maximum rate at the lower air velocities and this rate would be the same for all samples unless it exceeded the maximum rate of transfusion of moisture. Furthermore, this drying rate would be maintained in every case until it exceeded the maximum rate of transfusion of the moisture. Reference to the drying rates of, say, Blackwood and Matai shows that such a state of conditions does not exist, however, and the indications are that the rate of removal of moisture from the surface is dependent to a limited extent on the velocity of the circulating air. For example, at a velocity of 30 feet per minute the drying rate of the Blackwood from 90% to 80% moisture content was only 3.5 grams per hour, whereas under the same conditions the drying rate of the Matai was 10.9 grams per hour - a figure comparable with the drying rate of the blackwood at an air velocity of 292 feet per minute.

In forced circulation kilns of modern design air velocities usually range between 200 and 500 feet per minute, these velocities having been adopted more or less empirically in order to reduce the lag in the drying rate from the entering to the leaving air side of the stack to a reasonably small value. The present tests indicate that even at 200 feet per minute the air velocity is well above that at which the "surface resistance" ceases to depend on the velocity. This may not be the case for all timbers and all drying conditions but the present test embraced a reasonably wide and representative range of timbers and drying rates.

It is not possible from the present results to explain the exact nature of the so-called "surface resistance" or why it should be affected by the velocity of the air.

EXPERIMENT 3.

THE RELATION BETWEEN THE QUANTITY OF AIR CIRCULATED AND THE LAG IN DRYING FROM THE ENTERING TO THE LEAVING AIR SIDE OF A KILN CHARGE OF TIMBER.

INTRODUCTION.

In the drying of a stack of timber of commercial proportions, the heat necessary must be carried to the timber by the circulating air. It follows that the temperature and relative humidity of the circulating air must change as the air moves throûgh the stack, and, furthermore, as the rate of drying is a function of the temperature and relative humidity, there must be a change in the rate of drying from the entering to the leaving air side of the stack. This change is a "lag".

Some lag is inevitable, but it is dependent on the volume of air circulated as well as on the rate of drying, and can be kept within reasonable limits by circulating sufficient air.

In most commercial kilns of modern design the problem of lag is overcome to a large extent by providing for a periodic reversal of the circulation. However, even under these circumstances, it is undesirable to have a large lag for the following two main reasons. First, a large lag slows up the net drying rate because, when the circulation is reversed each time, the moisture content of the boards on the then entering air side of the stack is higher than would be the case if the lag were kept small. Second, despite the reversal of circulation, there is, on account of the non-straight line relation between lag and distance across stack, an inevitable lag in the drying rate at the centre of the stack. This must be kept reasonably small by keeping the overall lag small.

In the design of a kiln for drying any particular class of stock, it is desirable to be able to calculate the quantity of air required for efficient and reasonably uniform drying. A number of tests has been carried out to determine experimentally the change in air conditions and the drying rate across a stack of timber 5 feet wide with various quantities of air being circulated. The results obtained have been compared with the theoretically deduced values.

MATERIAL USED.

Species: Blackwood (*Acacia melanoxylon*).

Source of Supply: Victorian Forests Commission.

Condition: Free from degrade. Moisture content approximately 100%

Quantity and Preparation: Eight flitches 8"x 5"x 7 feet long were available for the work. These were sawn into 8"x 1" boards, each flitch yielding four such boards which, in turn, were marked off and cut into four 18-in.long sample boards. From two flitches the sample boards were cut down from 8-in. to 6-in. in width. The sample boards were divided into sixteen groups, each group containing one board from each flitch.

The material was further divided into six kiln runs, as far as possible each run containing three of the above groups. For the sixth run, the necessary material was made up from the 2-in. strips sawn from some of the original 8-in. sample boards and from some green blackwood which had been left over from other experiments.

APPARATUS USED.

Kiln. The kiln used is described in Experiment 1, except that in the present tests as in Experiment 2, the air after moving through the timber was not blown into the room but returned to the fan for re-circulation. At the same time, a small proportion was allowed to spill away through the upper vents and was replaced by fresh air through the lower vents to prevent the humidity rising above that required. In this kiln, stacks of timber 18-in. wide by 16-in. high by 5 feet long were built as shown in Figure 3. With the exception of three rows, the stacks were built of dummy 1-in. boards. The excepted three rows consisted of the 1-in. green blackwood sample boards, each row being built up of one of the groups of boards described previously. In all runs the sample boards from the different flitches were placed in the same order in the kiln. For the first four runs 1-in. separating strips were used; for the remaining two runs $\frac{3}{4}$-in. strips were used.

Anemometer. The velocity of the air circulating between the test rows was measured in each run by means of the special low speed anemometer and according to the method described in Experiment 1. A small mirror fitted to the front of the dial enabled readings to be taken through the inspection doors provided in the main kiln doors. Corrections were made for the temperature of the air. (See Ower[1]).

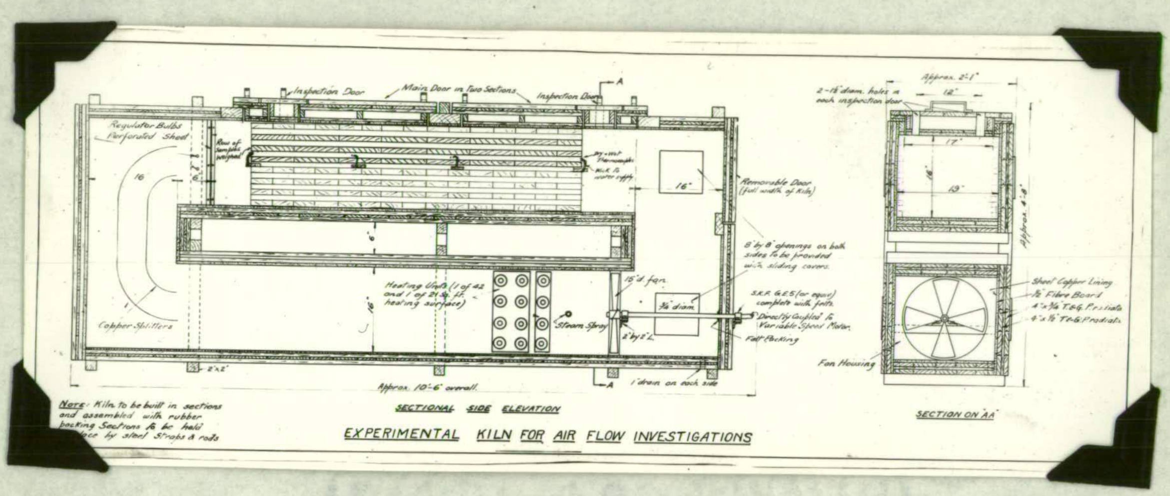


FIGURE 3.

Thermocouples and Potentiometer. The thermocouples used for the dry and wet bulb temperature measurements were of eureka-copper. The wet bulbs were similar to the dry but wrapped round with cotton gauze wicks dipping into petri dishes containing water.

Four sets of dry and wet bulbs were placed in the kiln between the two lower rows of sample boards. They were located at the entering air side of the stack, 18-in. along, 3 feet along, and at the leaving air side respectively. As will be seen from

Figure 3, the petri dishes were located in the opening below that in which the thermocouples themselves were placed so that there would be no interference with the circulating air in this opening. Small holes were made where necessary in the lower row of sample boards to allow the wicks to pass from the wet bulb thermocouples to the water supplies. The thermocouples were offset one from the other across the width of the kiln.

The thermocouples produced an E.M.F. of approximately .0242 millivolts per ^{o}F. difference in temperature between the hot and cold junctions.

The potentiometer used was the laboratory instrument, (No.L-50785) manufactured by the Cambridge Instrument Company and known as the Workshop Pattern. It is described in the Company's list No.191. Readings were taken to 0.01 millivolt and were probably accurate to within $\pm$ 0.01 or approximately $\frac{1}{2}^{o}$F. A glass thermometer fitted on top of the instrument was used to read the temperature of the cold junction. The various thermocouples were connected in turn to the potentiometer by a dial switch.

PROCEDURE.

The middle row of sample boards was used in each run to measure the drying rate and each board from this row was weighed twice daily throughout the duration of the run.

The kiln control instrument was set at 140°F. dry bulb and 120°F. wet bulb throughout the six runs. The fan speeds and strips used in the different runs were as follows:-

Run	Fan Speed		Separating Strips.
1	860		1-in.
2	1700		1-in.
3	860	(using fan inlet baffle)	1-in.
4	1260		1-in.
5	860	-do-	$\frac{3}{4}$-in.
6	1700		$\frac{3}{4}$-in.

Potentiometer readings were taken during the day-time only. They were made every hour during the first two or three days of each run when the conditions were changing fairly rapidly, and every other hour during the remainder of the run. At first some difficulty was experienced in obtaining satisfactory readings on account of the fluctuating kiln conditions, such fluctuations (of the order of ±3°F.) occurring before the control instrument comes into action. This difficulty was overcome by using hand valves in series with the automatically operated valves and so throttling the steam supply to the automatic valves that when they opened 20 or 30 minutes were required to elapse before the kiln conditions were changed sufficiently for them to be closed again. During the period when the valves were open, potentiometer readings were taken of the eight thermocouple E.M.Fs. in order and then in the reverse order. The sixteen readings took only about 5 minutes and the average of the two readings for each thermocouple was assumed correct.

Each run was continued for one week. The average moisture content of the charges was still about 30% at the end of the drying period, but the drying rate had become quite slow and from the point of view of change in conditions there seemed little to be gained by continuing beyond this stage. As the boards throughout the width in each charge were not matched, the question of net final lag could not be investigated satisfactorily. At the end of each run moisture content sections were cut from the sample boards from the centre row of each charge.

RESULTS.

Change in Drying Conditions from the Entering to the Leaving air side of the Stack. - Six sets of curves are given in Figure 4, showing the change in dry bulb temperature, the change in wet bulb temperature, and the change in relative humidity from the entering to the leaving air side of the stack. The curves give the average figures obtained during drying from the initial moisture content of 100% to an average of 80% in each of the six respective runs. These curves are typical of the changes and it has not been considered necessary to include the curves for the remaining portions of the runs. The actual changes between entering and leaving air conditions for successive stages of drying in each run are, however, given in Table 2, page 28.

[redacted]

TABLE 2.

ENTERING AND LEAVING AIR CONDITIONS AND A COMPARISON OF THE CALCULATED AND ACTUAL AIR VELOCITIES.

Run	Stage of Drying (stack average)	Average drying rate % moisture content per hour.	Average conditions of Entering Air: Measured Temperature °F. Dry Bulb	Average conditions of Entering Air: Measured Temperature °F. Wet Bulb	Average conditions of Entering Air: Relative Humidity %	Average conditions of leaving air.: Measured Temperature °F. Dry Bulb	Average conditions of leaving air.: Measured Temperature °F. Wet Bulb	Measured Relative Humidity %	Calculated Relative Humidity %	Air velocity feet per minute: Measured	Air velocity feet per minute: Calculated
1	From 100% to 80% M.C.	1.39	140	120	54	132	121	71	72	320	292
	" 80% to 60% "	.65	140	120	54	136	120½	62	64	"	303
	" 60% to 40% "	.35	140	120	54	137½	120½	60	60	"	281
2	" 100% to 80% "	1.70	141	120	53	136	121	63	69	547	497
	" 80% to 60% "	.69	141	120	53	138	120½	59	64	"	540
	" 60% to 40% "	.35	141	120	53	139½	120½	56	59	"	424
3	" 100% to 80% "	1.25	140	120	54	130	121	76	77	146	178
	" 80% to 60% "	.63	140	120	54	134	120½	66	68	"	131
	" 60% to 40% "	.35	140	120	54	135	120½	64	66	"	130
4	" 100% to 80% "	1.54	140	120	54	134	120½	66	68	464	408
	" 80% to 60% "	.66	140	120	54	137	120½	60	61	"	411
	" 60% to 40% "	.35	140	120	54	138	120	58	58	"	338
5	" 100% to 80% "	1.13	140	120	54	124	122	94	95	171	174
	" 80% to 60% "	.62	140	120	54	132	121	71	72	"	143
	" 60% to 40% "	.35	140	120	54	135	120½	64	66	"	173
6	" 100% to 80% "	1.67	140½	120	54	134	121	67	68	681	634
	" 80% to 60% "	.68	140½	120	54	138	120	58	60	"	596
	" 60% to 40% "	.35	140½	120	54	139	120	56	57	"	565

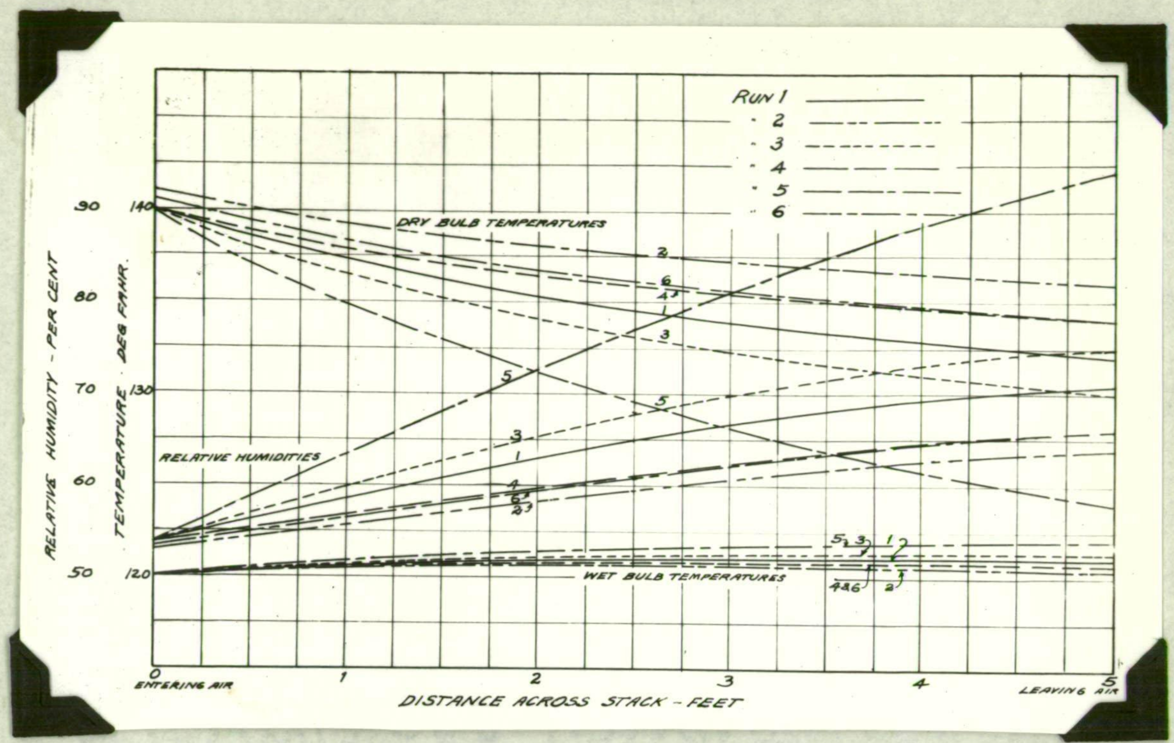


FIG.4. Change in air conditions from entering to leaving air side of stack.

<u>Change in Drying Rate from the Entering to the Leaving air side of the Stack</u>. While the average drying rate at different positions across a commercial sized stack of timber probably shows a regular variation, the variation across a single row may be far from regular due to the different "nature" of the boards in the row. This lack of matching of the sample boards in the test rows of the experimental kiln charges considered gave some unexpected results. Thus, it was found that a board about half way from the entering air side dried more rapidly than the board at the entering air side

On the other hand, the boards at corresponding positions in the stacks were matched in all runs and it was found that the drying rates of the boards at the entering air sides were practically the same in all runs. This fact confirms the results found previously and described in Experiment 2. The rates of drying of the sample boards on the leaving air sides of the stacks varied in different runs more or less according to the drying conditions which were present there. For any one stage of the drying, that is, between the same moisture content limits, the drying rate was found to be approximately proportional to the difference between the local dry and wet bulb temperatures. This relation is shown graphically in Figure 5 for the drying of the samples on the leaving air side from 100% to 80% moisture content.

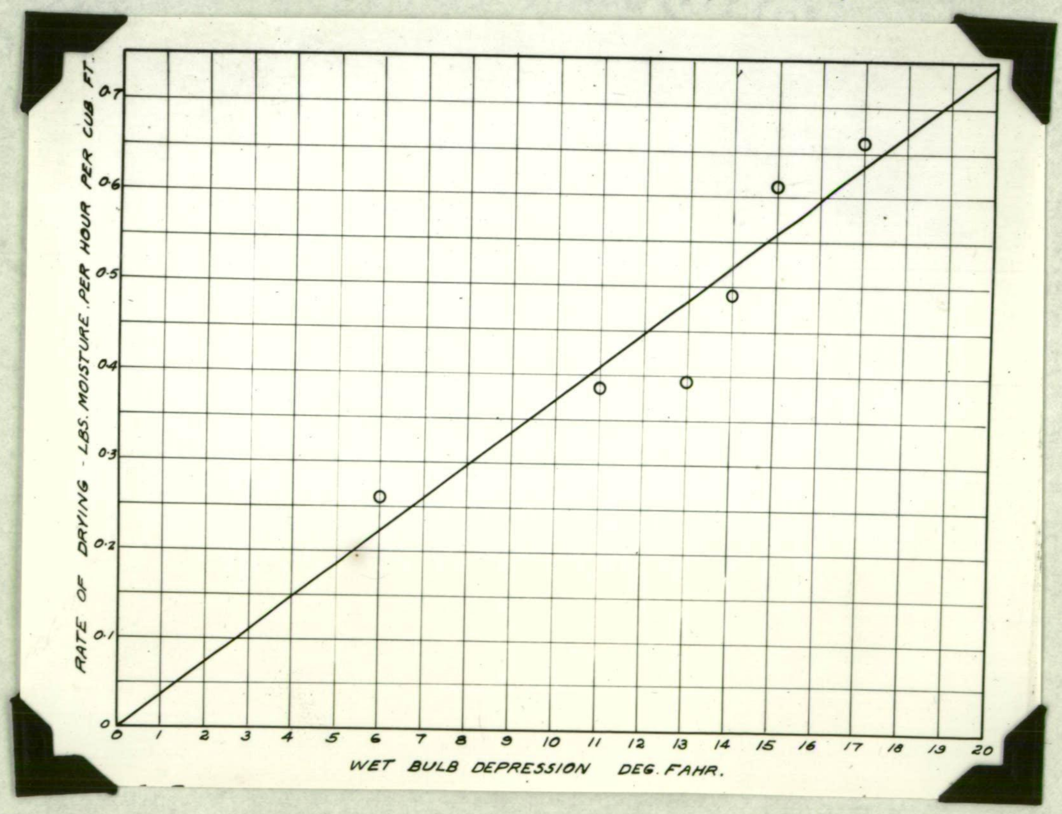


FIG.5. Relationship between rate of drying of sample at leaving air side of stack and wet bulb depression at this point.

By extending the curves somewhat, it has been possible to deduce from the results given on Figure 4 what would have been the drying rates at different positions across the stack if all the boards had been exactly matched with those at the leaving air side. Curves obtained in this way showing the change in drying rate from the entering to the leaving air sides of the stacks in the different runs during the drying from the initial moisture content of 100% to an average of 80% are given in Figure 6.

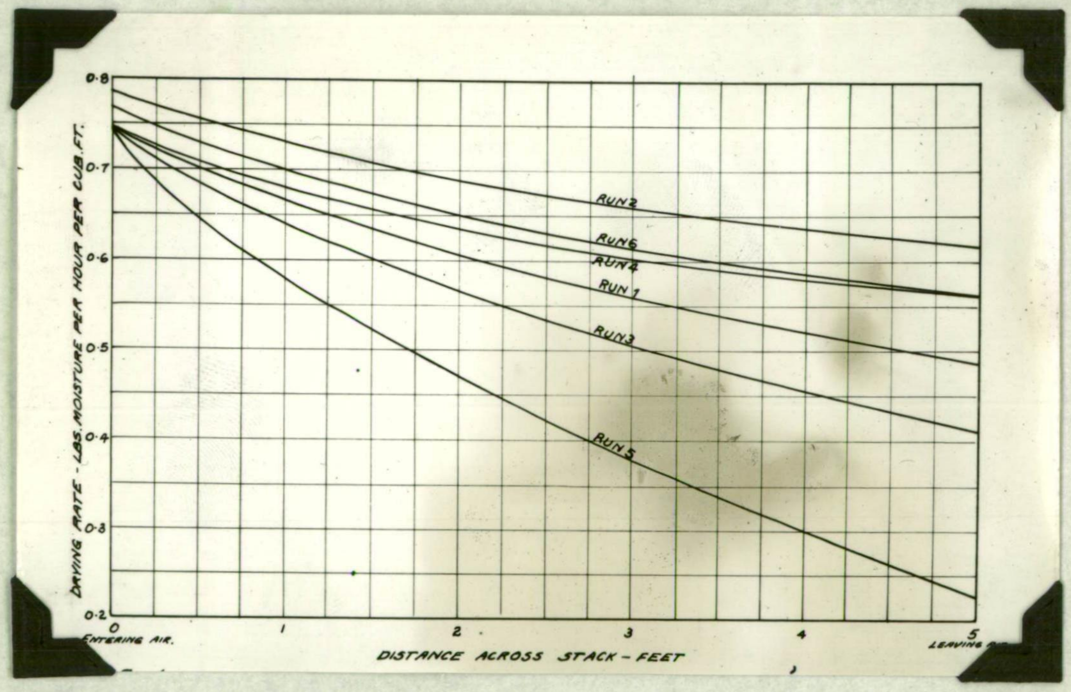


FIG.6. Change in drying rate from entering to leaving air side of stack. (Calculated on the assumption that all boards in stack matched with board at leaving air side).

Quantity of Air Required. The theoretical quantity of air required for, and the change in conditions caused by the removal of moisture during various stages of drying have been calculated by the method described in Appendix 1. It will be seen that, provided the velocity of the air is above a certain minimum figure (discussed in Experiment 2), the lag in drying is influenced by the quantity and not the velocity of the air. In speaking of quantities of air, however, details of the stack through which the air is circulated must also be specified and it is often simpler to use air velocities, at the same time bearing in mind the size of separating strip used.

The calculated velocities in the present tests and those actually measured are given in Table 2. It is necessary for the calculations to know either the leaving air temperature or relative humidity from which the other can be calculated. The measured leaving air temperature has been used in the present calculations and the calculated as well as the measured leaving air relative humidity is given in the table.

DISCUSSION OF RESULTS.

Change in Drying Conditions from the Entering to the Leaving Air Side of the Stack. An examination of the curves for dry and wet bulb temperature variations from the entering to the leaving air side of the stack shows that the wet bulb temperature changes by much less than the dry bulb temperature. For approximately every 8°F. fall in dry bulb temperature, the wet bulb temperature increases by 1°F. While this approximate relation between the dry and wet bulb temperature changes may not be the same for all temperatures the relation is probably similar in most cases.

<u>Change in Drying Rate from the Entering to the Leaving Air Side of the Stack</u>. The comparison of drying rates from one side to the other of a stack of timber, must, if the results are to be truly indicative of the changed drying conditions, be made at the instant when the drying is commenced, assuming that at this moment the moisture content of all the boards is at least approximately the same.

Immediately the moisture content across the stack becomes uneven the boards with the higher moisture content at the leaving air side commence to dry more quickly than they would under the same conditions if they were at the same moisture content as the boards at the entering air side. It generally happens that, toward the end of a run, the drying rate at the leaving air side of a stack is greater than at the entering air side because the moisture content at the leaving air side is higher than at the entering air side, although the drying conditions are less severe.

For this reason, we find any variation in moisture content tending to become less towards the conclusion of a kiln run. Eventually all the material would dry to the same moisture content, namely, the equilibrium moisture content of the conditions used, but the period required for this to happen would in most cases be very considerable.

In Figure 4 the average variation in drying rate across the width of the stack in each run during drying from the initial moisture content of 100% to an average moisture content of 80% has been given. At the beginning of the drying the variation would have been greater than that shown, whereas, when the average moisture content was approaching 80% the variation would have been less than that shown.

Quantity of Air Required. Generally speaking, the agreement between the measured and the calculated air velocities is satisfactory. In most cases, however, the calculated velocity is from 10% to 20% less than that measured. This is probably due to the fact that the calculated figure gives the *minimum* velocity required, whereas actually it appears that some of the air passes through the stack without accomplishing the desired result. This conclusion is further substantiated by the fact that the actual relative humidity of the leaving air was in nearly all cases somewhat less than that calculated.

PRACTICAL APPLICATION OF RESULTS.

In the application of the calculations in Appendix 1 for determining the quantity of air required in commercial kilns, the first step to decide on is the allowable initial lag in the drying rates from the entering to the leaving air side of the stack. This figure will obviously depend on the class of material being dried, on the rate of drying, and on whether or not the circulation is periodically reversed. Where a fast rate of drying is maintained throughout the whole run there will be little opportunity for the moisture content to become more uniform toward the conclusion of the run. On the other hand, in most cases the drying in the latter stages of a run is comparatively slow, and the tendency is for the moisture content to become more uniform throughout the charge. In modern kilns in which the circulation is periodically reversed, a lag in drying rate at the leaving air side of 20% of the drying rate at the entering air side of the stack, for the first twelve hours of drying, should be a satisfactory allowance in most cases.

Next to be determined are a suitable drying schedule and the actual drying rates. Determinations of this nature are being carried on as rapidly as possible at the Forest Products Laboratory. The principal Australian timbers are being tested and in many cases already it is possible to obtain a suitable schedule and the drying rate which, in a commercial kiln, will correspond to the drying rate at the entering air side of the stack.

Furthermore, as the work of determining a suitable schedule usually involves a number of kiln runs at different initial drying conditions, it should, in most cases, be possible to determine an approximate relation between the rate of drying and the wet bulb depression. Having already decided on the drying rate which must be maintained at the leaving air side of the stack, this relation could then be applied in fixing the necessary approximate wet bulb depression at this side. In applying the calculations given in the Appendix, it is necessary to know either the leaving air temperature or its relative humidity as well as the temperature and relative humidity of the entering air. The leaving air temperature is probably the more easily determined and applied; it can be obtained approximately by the following procedure :-

If the wet bulb depression has changed by $x^{o}F.$, then it can be assumed, from the relationship shown in Figure 4, that the dry bulb temperature has fallen $(\frac{8}{9}x)^{o}F.$

The average drying rate of the stack can, with little error, be taken as the arithmetical average of the rates at the two sides of the stack.

Knowing the entering air conditions, the leaving air temperature and the average drying rate, the quantity of air required to evaporate 1-lb. of water can be calculated. Then from the basic density of the timber[x] and details of the stack the velocity of the air through the stack can be calculated.

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[x]Oven dry weight/soaked volume.

In practice, this calculated velocity should be increased by about 20 per cent.

EXPERIMENT 4.

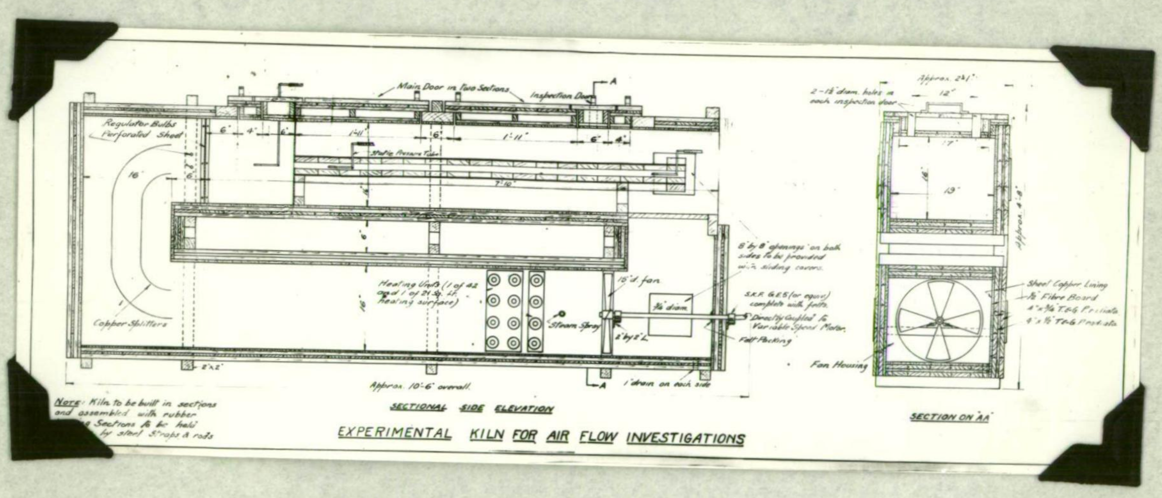
THE RELATION BETWEEN AIR FLOW AND FALL IN PRESSURE ACROSS A TIMBER STACK.

INTRODUCTION.

In the design of a forced circulation timber seasoning kiln, such as the cross shaft internal fan kiln, the first point to be decided upon is the quantity of air to be circulated. This depends largely on the class of timber to be dried and has been considered in detail in Experiment 3. Having decided on the quantity of air, however, the question of fan size and speed, and size of separating strips must be considered. The fan must be chosen to deliver the required quantity of air through a stack of definite dimensions and with a given thickness of separating strip. The complete consideration of the problem involves a knowledge of the relation between the air velocity and the resistance to flow for various sized strips and for timber of different degrees of surface roughness. With the object of establishing this relation the work of the present experiment has been carried out.

APPARATUS USED.

Kiln. - The main item of equipment used was the special kiln designed for this class of work and described in Experiment 1. In this kiln a rectangular duct 6 feet long, built up of 4-in. wide boards and separating strips, was arranged as shown in Figure 7. Special precautions were taken to ensure that the air was allowed to pass only through the duct, the outside of which was sealed with strong paper to prevent leakage. Ducts were constructed with separating strips $\frac{3}{8}$-in., $\frac{1}{2}$-in., $\frac{5}{8}$-in., $\frac{3}{4}$-in., $\frac{7}{8}$-in., 1-in., $1\frac{1}{4}$-in., and $1\frac{1}{2}$-in. thick and with timber of three different degrees of roughness. The different degrees of roughness are illustrated in Fig.8, and may be described as (a) smooth (planed) (b) average sawn, and (c) rough sawn.



EXPERIMENTAL KILN FOR AIR FLOW INVESTIGATIONS

Figure 7.

Anemometers. - The velocity of the air passing through the duct was measured at the exit end using the anemometers described in Experiment 1, and applying correction factors as for 2-in. thick timber, the centre of the anemometer being held over the centre of the opening. Readings were taken with the ordinary anemometer but all readings up to 500-ft. per minute were checked with the low speed anemometer. In all such cases the two instruments were in close agreement.

(a) Smooth (planed)

(b) Average sawn

(c) Rough sawn

<u>Figure 8</u>.

Static pressure tubes were arranged as shown in Figure 7 for connection to a manometer to enable measurements to be made of the static pressure difference between two points 5 feet apart, 6-in. in from each end of the duct. A third static tube was located in the open chamber on the entering air side of the duct. The static tubes used were of the hemispherical end type similar to the pitot tube described by Ower[1], page 27. As, however, the air velocities being employed were, for the most part, too low to be accurately measured with a pitot tube and manometer of the sensitivity available, and in this work were being measured with an anemometer, the hemispherical end of the tube was made solid. Static pressure differences only were measured. The tube used is shown in Figure 9.

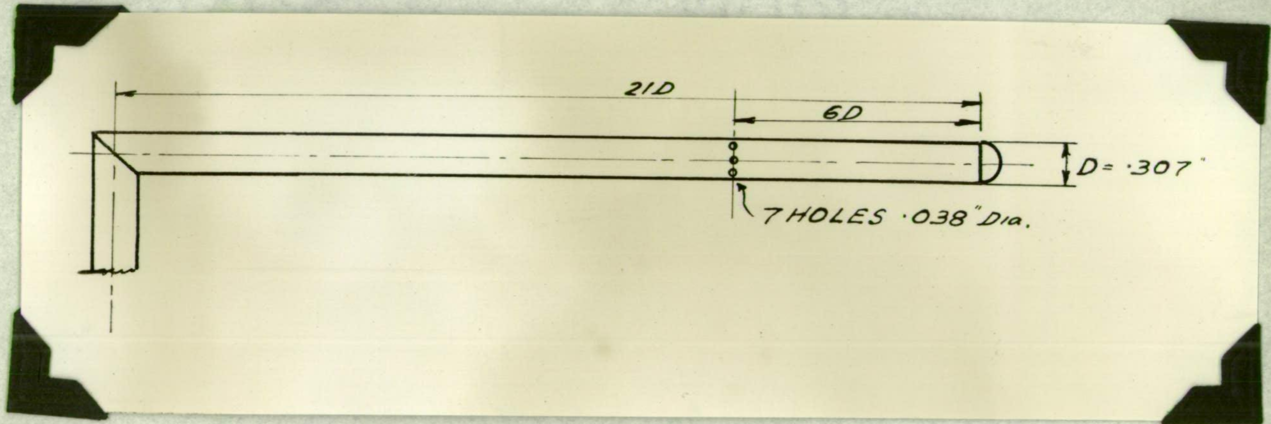


Figure 9.

Manometer. - The manometer employed for the static pressure difference measurements was of the direct lift type shown in Figure 10. In this gauge a large spun brass reservoir forms one leg of the U-tube, and is connected through rubber tubing to a short length of glass tubing mounted on a metal bracket at a small angle to the horizontal. The bracket is carried by a block which can be raised or lowered by means of a micrometer screw and dial. The gauge is filled with coloured alcohol whose specific gravity must be accurately determined.

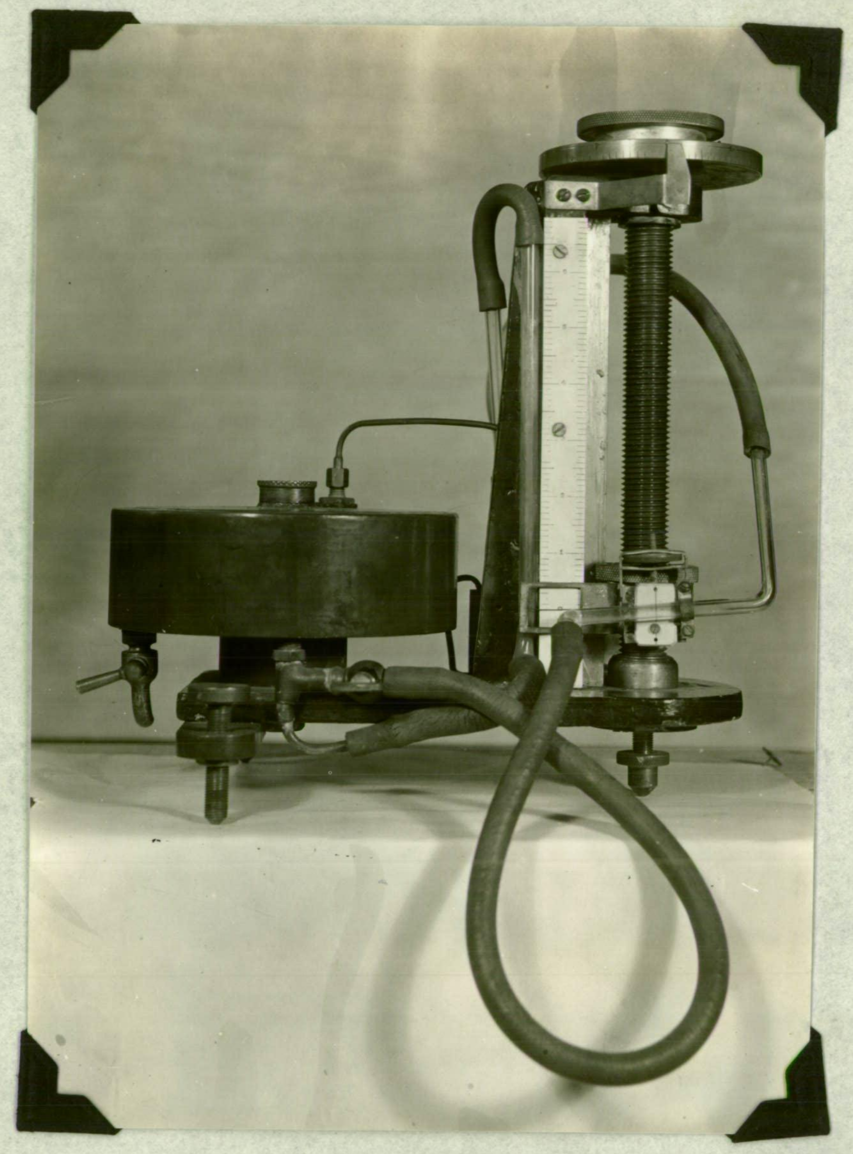


Fig.10. Direct lift Manometer.

The meniscus in the slanting tube with the gauge at zero is adjusted by a small screw which raises or lowers the tube indepently of the micrometer screw until the meniscus is tangent to a hairline engraved on the glass.

The alcohol under the action of the applied pressure difference tends to rise in the slanting tube, and the tendency is counteracted by raising the tube bodily by means of the micrometer screw, keeping the meniscus tangent to the hairline. The amount the tube is elevated is then the pressure difference in inches of alcohol. The sensitivity of the gauge can be varied by adjusting the slope of the inclined tube.

The micrometer is evidently a self standard whose precision depends only on the accuracy of the micrometer screw. The use of the large reservoir renders it necessary to observe one meniscus only. The range of the gauge can be made quite large, that illustrated having a range of 10 inches of alcohol.

PROCEDURE.

Ducts were constructed using the different sized strips mentioned previously and with boards of the three different degrees of roughness. In each set-up a series of velocity and pressure difference readings were taken with six different air velocities, the velocity being varied by varying the fan speed and baffling the fan intake as required. Approximately the same set of fan speeds and baffles were used with the different ducts.

In each case four anemometer readings were taken (and as explained previously in some cases with two different instruments) and the average of these used for computing the air velocity. Anemometer readings were taken by timing with a stop watch the period required for the instrument to record 100 feet.

Static pressure differences were measured -

(a) between the two tubes 5 feet apart in the duct,
and
(b) between the tube outside the duct on the entering air side and the tube in the duct 5 feet 6 inches from the inlet end.

From (a) the change in pressure per foot of duct could be determined; from (b) and (a) the entrance loss of pressure was determined.

RESULTS.

The results are given in Tables 3, 4 and 5. The air velocities given are the actual, the anemometer readings having been corrected. The pressure difference readings are in inches of water, the actual gauge readings having been multiplied by the specific gravity of the alcohol at the time of the test.

TABLE 3.

RESULTS OF TESTS WITH PLANED BOARDS.

Size of Separating Strips. ins.	Air Velocity ft. per min.	Manometer Reading (a)	Pressure Loss per foot of duct = $\frac{a}{5}$	Manometer Reading (b)	Entrance Pressure Loss = $\left(b - \frac{5\frac{1}{2}a}{5}\right)$	Ratio - $\frac{\text{Ent. press. loss}}{\text{Velocity}^2}$
⅛"	2154	.3425	.0685	.585	.209	4.5×10^{-8}
	1828	.2425	.0485	.403	.137	4.1
	1196	.105	.0210	.175	.060	4.2
	1079	.0855	.0171	.144	.050	4.3
	733	.039	.0078	.0665	.0235	4.4
¼"	2118	.281	.0562	.514	.205	4.3×10^{-8}
	1770	.1955	.0391	.340	.125	4.0
	1191	.0905	.0181	.1665	.067	4.7
	914	.050	.01	.0925	.0375	4.5
	668	.028	.0056	.050	.019	4.3
⅜"	2218	.272	.0544	.533	.234	4.5×10^{-8}
	1811	.1775	.0355	.356	.161	4.9
	1276	.0885	.0177	.165	.068	4.2
	1089	.0665	.0133	.123	.050	4.2
	750	.0295	.0059	.0575	.025	4.5
	549	.0165	.0033	.031	.013	4.3
¾"	2280	.255	.0510	.509	.229	4.4×10^{-8}
	1722	.1405	.0281	.2725	.118	4.0
	1225	.0705	.0141	.1475	.070	4.7
	1026	.053	.0106	.106	.048	4.6
	832	.0315	.0063	.065	.031	4.5
	486	.012	.0024	.023	.010	4.2
⅞"	2344	.2305	.0461	.479	.226	4.1×10^{-8}
	1710	.1295	.0259	.265	.123	4.2
	1169	.0575	.0115	.130	.067	4.9
	955	.036	.0072	.0775	.038	4.2
	614	.0165	.0033	.035	.017	4.5
	428	.008	.0016	.0165	.0075	4.1
1"	2239	.2035	.0407	.419	.195	3.9×10^{-8}
	1660	.1065	.0213	.221	.104	3.8
	1148	.053	.0106	.121	.063	4.8
	851	.028	.0056	.064	.033	4.6
	552	.0115	.0023	.0255	.013	4.3
	352	.005	.0010	.011	.0055	4.5
1¼"	2148	.1625	.0325	.378	.199	4.3×10^{-8}
	1560	.086	.0172	.1865	.092	3.8
	1112	.0695	.0139	.1265	.050	4.0
	826	.0225	.0045	.053	.028	4.1
	472	.0075	.0015	.017	.009	4.1
	304	.003	.0006	.0075	.004	4.3
1½"	1928	.115	.0230	.275	.148	4.0×10^{-8}
	1445	.066	.0132	.1625	.090	4.3
	984	.0295	.0059	.075	.0425	4.4
	698	.0125	.0025	.033	.019	3.9
	378	.0045	.0009	.0115	.0065	4.6
	243	.002	.0004	.0045	.0025	4.2

TABLE 4.

RESULTS OF TESTS WITH AVERAGE SAWN BOARDS.

Size of Separating Strips	Air Velocity ft. per min.	Manometer Reading (a)	Pressure Loss per foot of duct = $\frac{a}{5}$	Manometer Reading (b)	Entrance Pressure Loss = $(b - \frac{54a}{5})$	Ratio - $\frac{\text{Ent.press. loss}}{\text{Velocity}^2}$
1/8"	2163	.456	.0912	.721	.220	4.7×10^{-8}
	1730	.293	.0586	.460	.138	4.6
	1268	.1525	.0305	.240	.072	4.5
	1112	.1195	.0239	.189	.058	4.8
	944	.085	.0170	.1335	.039	4.4
	773	.056	.0112	.086	.0245	4.1
1/4"	2178	.3775	.0755	.596	.184	3.9×10^{-8}
	1652	.216	.0432	.358	.120	4.4
	1250	.1195	.0239	.279	.065	4.2
	1074	.089	.0178	.146	.048	4.2
	863	.059	.0118	.097	.032	4.3
	586	.028	.0056	.048	.017	4.9
3/8"	2198	.330	.0660	.575	.212	4.4×10^{-8}
	1738	.197	.0394	.362	.145	4.8
	1274	.111	.0222	.190	.068	4.2
	968	.064	.0128	.1135	.043	4.6
	708	.034	.0068	.059	.0215	4.3
	555	.019	.0038	.041	.019	4.7
3/4"	2249	.3085	.0617	.561	.222	4.4×10^{-8}
	1660	.1695	.0339	.3045	.118	4.3
	1312	.103	.0206	.192	.079	4.6
	1028	.056	.0112	.1065	.045	4.3
	658	.0255	.0051	.0475	.0195	4.5
	443	.0115	.0023	.0215	.009	4.6
7/8"	2244	.273	.0546	.522	.222	4.4×10^{-8}
	1552	.133	.0266	.259	.113	4.7
	1202	.0755	.0151	.141	.058	4.0
	951	.0495	.0099	.0955	.041	4.5
	646	.022	.0044	.0435	.0195	4.7
	425	.010	.0020	.019	.008	4.5
1"	2203	.245	.0490	.478	.209	4.3×10^{-8}
	1718	.141	.0282	.279	.124	4.2
	1096	.060	.0120	.112	.046	3.8
	923	.0405	.0081	.0815	.037	4.4
	528	.0135	.0027	.028	.013	4.7
	347	.006	.0012	.012	.0055	4.6
1¼"	2042	.1735	.0347	.383	.192	4.6×10^{-8}
	1560	.1025	.0205	.205	.092	3.8
	1099	.0505	.0101	.1095	.054	4.5
	828	.029	.0058	.063	.031	4.5
	463	.0085	.0017	.019	.0095	4.4
	302	.0035	.0007	.008	.004	4.4
1½"	1820	.1255	.0251	.257	.119	3.6×10^{-8}
	1374	.0705	.0141	.1505	.073	3.9
	989	.0365	.0073	.081	.041	4.2
	695	.017	.0034	.0375	.019	4.0
	452	.008	.0016	.017	.008	4.0
	263	.0025	.0005	.0055	.003	4.3

TABLE 5.

RESULTS OF TESTS WITH ROUGH SAWN BOARDS.

Size of Separating Strips.	Air Velocity ft. per min.	Manometer Reading (a)	Pressure Loss per foot of duct = $\frac{a}{5}$	Manometer Reading (b)	Entrance Pressure Loss = $(b - \frac{5a}{5})$	Ratio - $\frac{\text{Ent. press. loss}}{\text{Velocity}^2}$
⅛"	1886	.416	.0832	.700	.142	4.0×10^{-8}
	1552	.281	.0562	.422	.113	4.7
	1086	.131	.0262	.203	.059	5.0
	908	.0945	.0189	.1435	.0395	4.8
	730	.055	.0110	.085	.0245	4.6
¼"	1977	.376	.0752	.570	.156	4.0×10^{-8}
	1574	.237	.0474	.380	.119	4.8
	1030	.103	.0206	.155	.042	4.0
	836	.067	.0134	.107	.033	4.7
	627	.038	.0076	.0615	.0195	4.8
⅜"	2014	.338	.0676	.546	.174	4.3×10^{-8}
	1578	.206	.0412	.340	.114	4.6
	1127	.1095	.0219	.1835	.065	5.1
	955	.076	.0152	.126	.042	4.6
	708	.044	.0088	.068	.020	4.0
	520	.0225	.0045	.038	.013	4.8
⅝"	2004	.304	.0608	.490	.156	3.9×10^{-8}
	1549	.183	.0366	.298	.098	4.1
	1054	.085	.0170	.138	.0445	4.0
	904	.063	.0126	.1025	.0335	4.1
	655	.0325	.0065	.055	.019	4.4
	443	.015	.0030	.0255	.009	4.6
⅞"	1968	.2785	.0557	.452	.146	3.9×10^{-8}
	1614	.186	.0372	.321	.117	4.5
	1072	.081	.0162	.144	.055	4.8
	925	.060	.0120	.1035	.0375	4.4
	514	.0185	.0037	.0305	.0105	4.0
	398	.011	.0022	.0195	.0075	4.7
1"	1936	.248	.0496	.434	.161	4.3×10^{-8}
	1514	.150	.0300	.261	.096	4.2
	1057	.072	.0144	.130	.051	4.6
	783	.041	.0082	.0715	.0265	4.3
	347	.008	.0016	.014	.005	4.2
1¼"	1936	.218	.0436	.404	.164	4.4×10^{-8}
	1507	.138	.0276	.261	.109	4.8
	1007	.060	.0120	.1115	.0455	4.5
	776	.035	.0070	.0665	.028	4.7
	433	.0105	.0021	.0205	.009	4.8
	279	.005	.0010	.009	.0035	4.5
1½"	1871	.191	.0382	.392	.182	5.2×10^{-8}
	1413	.1105	.0221	.220	.098	4.9
	1000	.0545	.0109	.101	.041	4.1
	607	.020	.0040	.035	.015	4.1
	366	.007	.0014	.0145	.0065	4.9
	209	.0025	.0005	.005	.002	4.6

DISCUSSION OF RESULTS.

List of Symbols Used. - The symbols used in the following discussion are set out below :-

a = $\frac{1}{2}$ long side of the rectangular duct

b = $\frac{1}{2}$ short side of the rectangular duct

A = long side of the rectangular duct.

B = short side of the rectangular duct.

p = fluid pressure at any specified point.

μ = co-efficient of viscosity.

m = mean hydraulic depth = cross section divided by wetted perimeter,

$$m = \frac{AB}{2(A+B)} = \frac{ab}{a+b}$$

h = pressure loss in inches of water per foot length of duct.

l = length of duct in feet.

H = pressure loss in inches of water in length l of duct.

H_T = total pressure loss across duct = entrance loss + duct loss.

v = mean velocity flow, feet per second.

V = mean velocity flow. feet per minute.

Q = quantity per second.

ρ = density of fluid.

g = acceleration due to gravity.

Pressure Loss in Duct. - The logarithm of the velocity has been plotted against the logarithm of the pressure loss per foot of length of duct for the three types of surfaces in Figures 11, 12 and 13 respectively. It will be seen that the points for each duct fall very closely to a straight line. The relation can evidently be expressed in the form

$$h = kV^n \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

where k and n are constants.

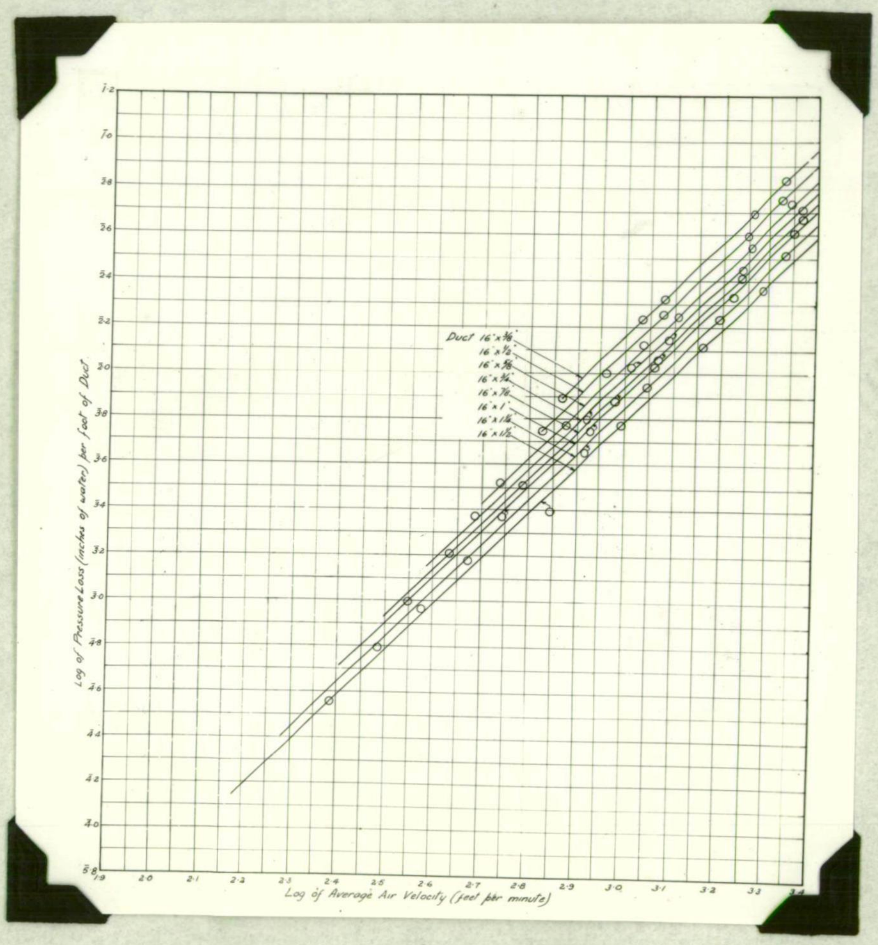


Fig.11. Relation between air velocity and pressure loss in ducts constructed of boards with smooth surfaces.

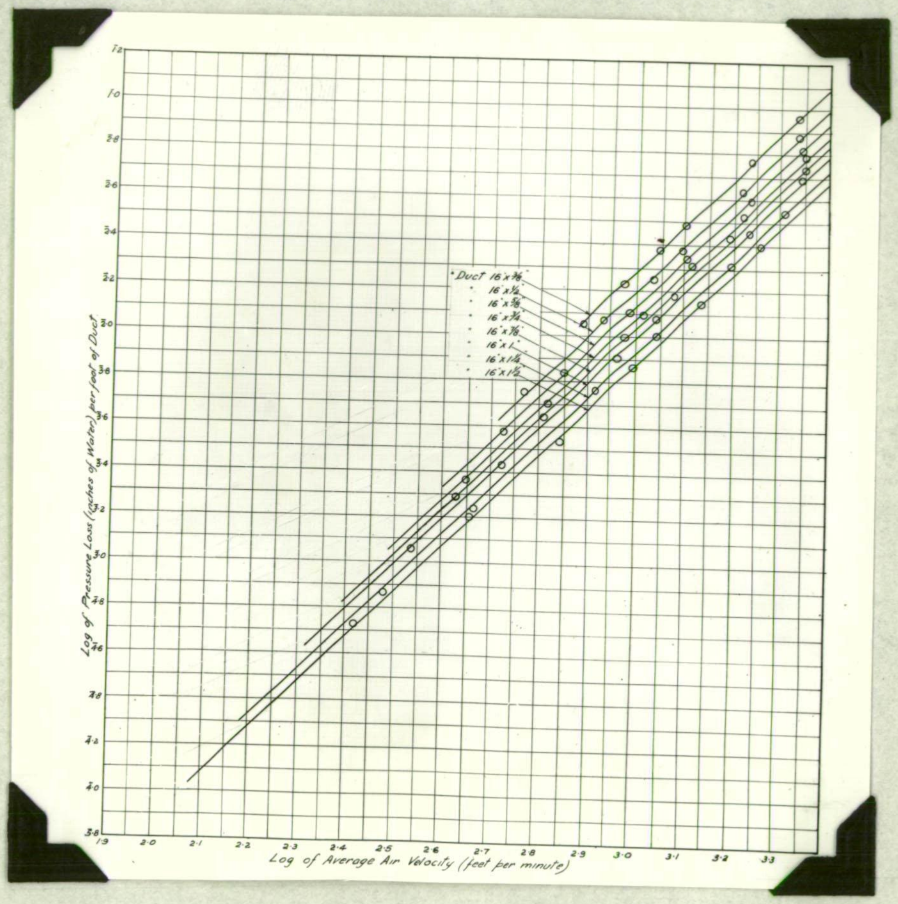


Fig.12. Relation between air velocity and pressure loss in ducts constructed of boards with average sawn surfaces.

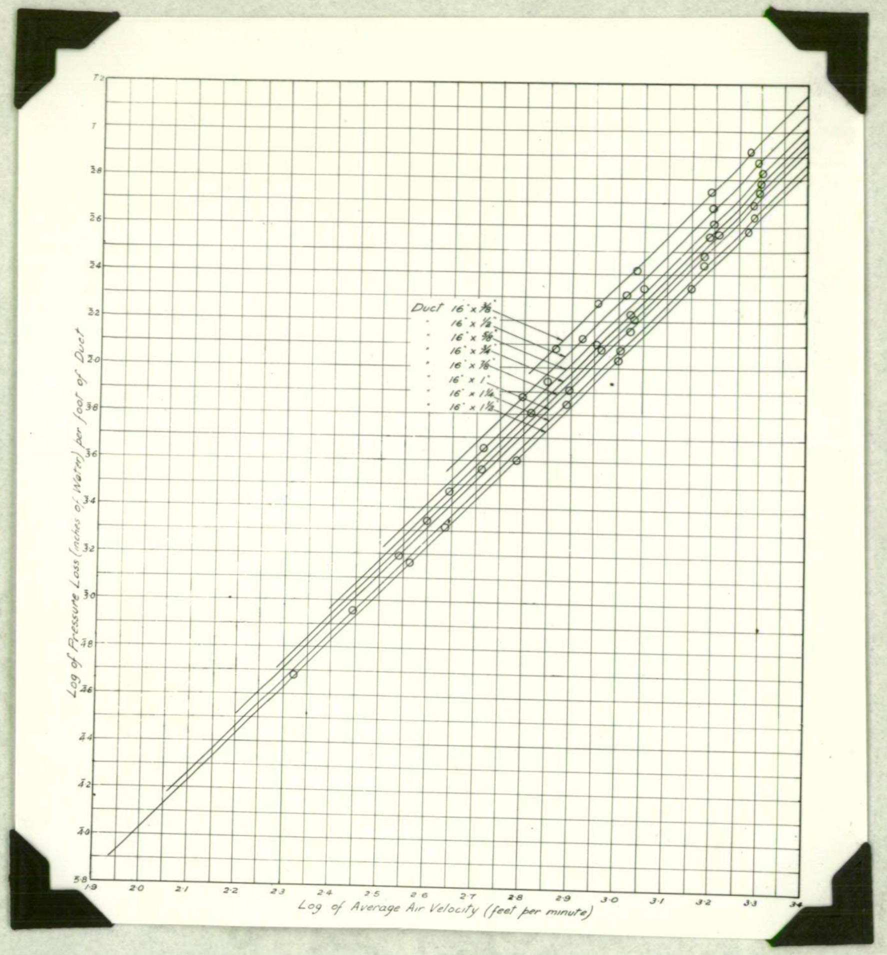


Fig.13. Relation between air velocity and pressure loss in ducts constructed of boards with rough surfaces.

Equation (1) can be written -

$$\log h = \log k + n \log V.$$

which is the equation of a straight line inclined at an angle θ to the axis of log V (where $\tan \theta = n$) and cutting off an intercept $= \log k$, on the axis of h. An examination of the curves will show that n is very close to 2 for the different sized ducts and for the three types of surfaces. k varies with the size of the duct and can be expressed closely as a function of the width of strip (or length of the shorter side of the duct = B). Actually it would probably be more accurate to express k as a function of the mean hydraulic depth:

$$\text{i.e.} \quad \frac{AB}{2(A + B)}$$

A is large compared with B, however, and (A + B) can be cancelled out with A leaving B/2.

If log k be plotted against log B for the three different surfaces the curves are nearly parallel straight lines and the relation can be expressed as -

$$k = fB^m \quad \ldots\ldots\ldots\ldots \quad (2)$$

where f and m are constants for any one type of surface. m is very close to (-0.61) for the three curves in the present tests.

Combining (1) and (2) and substituting the values for m and n, we have

$$h = fB^{-0.61}V^2 \quad \ldots\ldots\ldots\ldots \quad (3)$$

$$\text{or} \quad H = lfB^{-0.61}V^2 \quad \ldots\ldots\ldots\ldots \quad (4)$$

For smooth surfaces $f = 8.05 \times 10^{-9}$

For average sawn surfaces $f = 10.0 \times 10^{-9}$

For rough sawn surfaces $f = 12.2 \times 10^{-9}$,

When B is in inches, V in feet per minute, l in feet, H and h in inches of water.

The well known Fanning equation for isothermal turbulent flow in straight pipes is -

$$\frac{dp}{dL} = \frac{f'\rho V^2}{2gm}.$$

This can be written as -

$$\frac{dp}{dL} = \frac{f'\rho V^2 2(A + B)}{2g\ AB}$$

or for rectangular ducts in which A is very much greater than B -

$$\frac{dp}{dL} = \frac{f'\rho V^2}{2gB}$$

$$\text{or} \qquad h = f''B^{-1}V^2$$

which is similar to the equation deduced experimentally except that h varies as B^{-1} instead of as $B^{-0.61}$

<u>Critical Velocity.</u> - There is no indication from the velocity pressure curves obtained of any change from turbulent to streamline flow which would be evidenced by a change in slope of the curves. Apparently the lowest velocities used in the test were still above the critical velocity.

It is difficult to estimate the critical velocity for the flow of air through ducts such as the openings through timber stacks because of the short length of the duct. Cornish(3) states that even at a distance from the entrance of 400m (C.G.S. units) which corresponds to over 50 feet in the types of duct used in the present test, entrance disturbances cause a departure from what would otherwise be streamline flow, as the critical velocity is approached.

The intersections of the theoretical curves for streamline flow (see Appendix 2) with the experimental curves shown in Figures 11, 12, and 13, give critical velocities which are almost certainly too high. However, except in the case of the $3/8$-in. duct with the planed boards, in which the experimental data shows the turbulent flow to extend beyond that point, the experimental curves have been discontinued at the points where the theoretical stream flow curves would intersect them. Further experimental work appears desirable to determine the actual velocities at which transition from turbulent to streamline flow occurs in ducts of the type concerned. It seems probable, however, that in the majority of forced circulation kilns the air flow is turbulent in character.

<u>Entrance Loss to Duct</u>. - The pressure loss at the entrance to the opening has been given in Tables 3, 4 and 5 and also the ratio $\frac{\text{entrance loss}}{V^2}$. It will be seen that this ratio is approximately a constant, namely 4.4×10^{-8}.

<u>Total Pressure Loss, across Timber Stack.</u> - A timber stack can be considered as consisting of a number of rectangular ducts in parallel. The total pressure loss is the sum of the entrance loss and the friction loss in any one duct, and is expressed by -

$$H_T = flV^2B^{-0.61} + 4.4 \times 10^{-8}V^2$$

$$= (flB^{-0.61} + 4.4 \times 10^{-8})V^2 \quad \ldots\ldots\ldots (5)$$

The total head against which a kiln fan must work is the total "resistance head" which consists largely of the total pressure loss across the timber stack, and the velocity head. Other resistance losses occur in the kiln as the air is conducted from the fan to one side of the stack and returned from the other side. The extent of these losses will depend on the kiln design. It would, for instance, be considerably less in a cross shaft type of internal fan kiln in which the air leaves the fan in the same plane, as it moves through the timber, than in the longitudinal shaft type in which the air leaving the fan is at right angles to this plane and must be turned by means of baffles. The velocity head for air flow under low pressure differences can be determined with but slight error by the same formulae as are commonly used for the flow of water. The basic formula for such calculations is -

$$v = \sqrt{2gH_A} \quad \text{where } H_A = \text{head in feet of air causing flow}$$

$$\text{or} \quad V = 60\sqrt{2gH_A}$$

But we also have $\dfrac{12H_A}{H_W} = \dfrac{62.31}{W}$ or $H_A = 5.19\dfrac{H_W}{W}$

where H_W = pressure in inches of water

and W = weight of air in pounds per cub.foot.

$$\text{Then} \quad V = 60\sqrt{2 \times 32.2 \times 5.19\frac{H_W}{W}} = 1096.5\sqrt{\frac{H_W}{W}}$$

For standard air, 70°F. and 29.92 barometer, W = .07495.

$$\text{and} \quad V = 4005\sqrt{H_w}$$

$$\text{or} \quad H_w = \left(\frac{V}{4005}\right)^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

<u>Other Aspects of Results</u>. - At the highest fan speed used there is an increase in air velocity through the duct with decrease in spacing strip thickness down to approximately ¾-in. As the strips become smaller than this the velocity decreases. At the lowest fan speed the air velocity through the duct increases with decrease in spacing strip thickness down to the smallest strip used, i.e. ⅜-in., although obviously if the test had been continued with smaller strips a size would have been reached at which the velocity reached a maximum. This behaviour follows from a consideration of the factors influencing the velocity through the duct, namely, the size of strip and the resistance to flow.

The volume of air passing through the duct at all times decreasses with decrease in strip size.

These facts are of definite interest in determining the volume of air required for drying any particular class of timber.

<u>CONCLUSIONS</u>.

From the work carried out with regard to the relation between air flow and pressure loss, the following equations have been established.

(1) Pressure loss per foot of duct, h $= fB^{-0.61}V^2$

where $f = 8.05 \times 10^{-9}$ for smooth surfaces.

$= 10.0 \times 10^{-9}$ for average sawn surfaces.

$= 12.2 \times 10^{-9}$ for rough sawn surfaces.

B in inches, V in feet per minute, l in feet, h inches of water.

(2) Entrance loss to duct $= 4.4 \times 10^{-8}V^2$.

(3) Total loss across duct (in inches of water) -

$$H_T = (lf\,B^{-0.61} + 4.4 \times 10^{-8})\,V^2$$

(4) Total head against which kiln fan must work

= total pressure loss across stack

+ other resistance losses in kiln (which will depend on design of the kiln)

$+ \left(\frac{V}{4005}\right)^2$

The last term represents the velocity head, V being feet per minute.

EXPERIMENT 5.

THE EFFECT OF VARIOUS FEATURES OF KILN DESIGN ON THE DISTRIBUTION OF THE AIR OVER THE SIDE OF A STACK OF TIMBER IN A COMMERCIAL KILN.

INTRODUCTION.

The work of this investigation is grouped under two main divisions, -

(a) tests carried out in a special laboratory kiln, and

(b) tests in commercial kilns.

The present experiment consists of a series of tests made in commercial kilns to determine the effect of various distances between the walls of the kiln and the sides of the stack on the distribution of the air over the face of the stack.

Originally it was intended to investigate the effect of a number of factors in commercial kiln design on the distribution of the air over the side of the stack. These tests would have called for various changes in the actual kiln buildings and it was found impracticable to carry out the tests at private plants. The installation of a kiln of commercial proportions at the laboratory for this class of test has been recommended.

LOCATION OF TEST AND DESCRIPTION OF KILNS. ETC.

Location of Test: Messrs. Strahan & Davies,
Arden Street,
North Melbourne.

Description of Kilns, etc.- Two kilns only were used for the tests although there are four kilns of the same design at the plant. In kiln 1 (furthest from the reconditioning chamber) two separate charges were tested; in Kiln 2 (next to Kiln 1) a third charge was used.

The kilns are of the cross-shaft internal fan type and have been constructed from drawings supplied by the Division of Forest Products. The fans are spaced at 6-ft.6-in. centres and are 25-in. in diameter; they are rated to deliver approximately 4,000 cubic feet of air per minute at 500 r.p.m., the speed at which they are driven.

The stacks were 5-ft.6-in. high and their width was varied for test purposes. In Kiln 1, the space between the stack and the wall was 15-in. on one side and 13-in. on the other for the first charge, and 17-in. and 20-in. respectively for the second charge. In kiln 2 the two distances were 16-in. and 12-in. respectively. The stacks consisted of 1-in. Mountain ash, 7/8-in. separating strips being used.

Air velocities through the stack were measured by means of the special low speed anemometer according to the method described in Experiment 1. Other air velocities were measured by means of an ordinary anemometer.

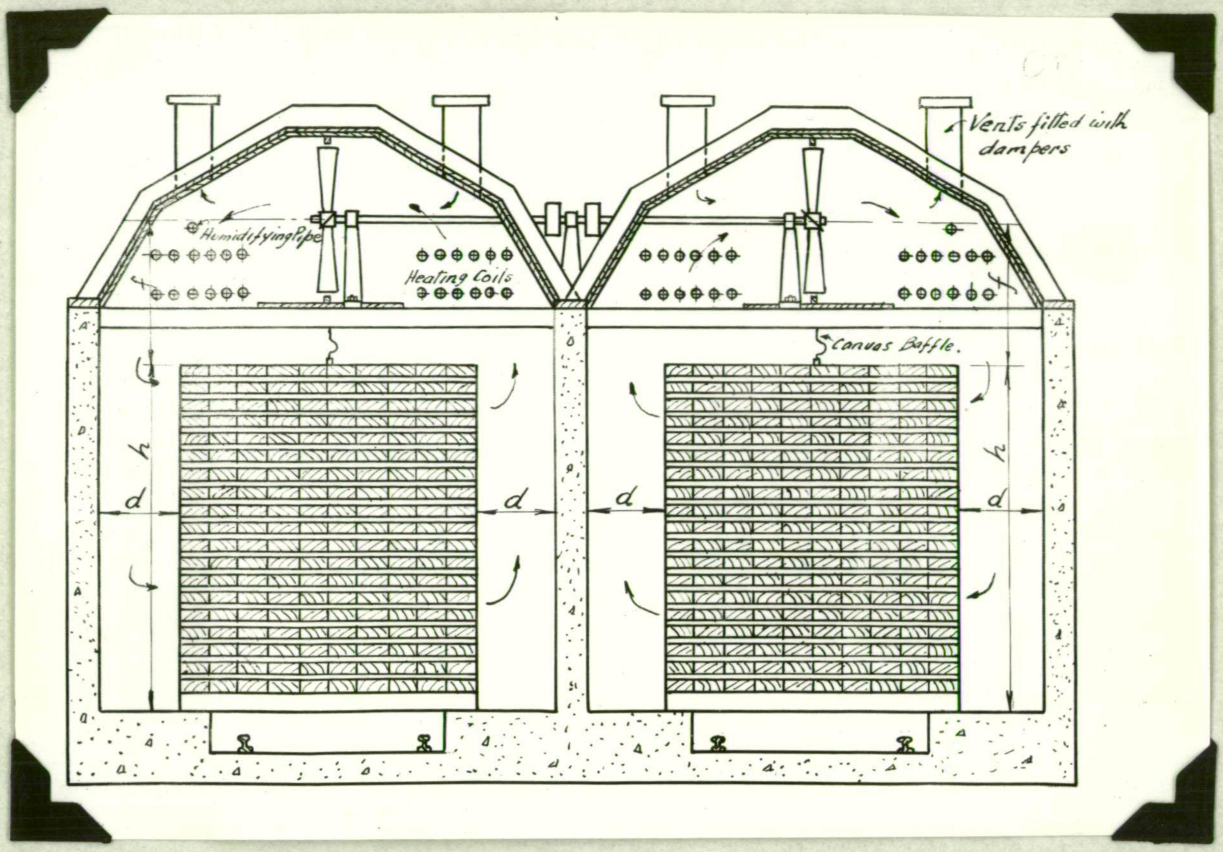


Figure 25a. Diagramatic Cross Section of Type of Kiln used in Experiment 5.

PROCEDURE.

In each kiln one fan was selected for test purposes. The selected fan was well away from the ends of the stacks and, as far as could be judged, was operating under entirely normal conditions.

The sides of the stack in the vicinity of the selected fan were marked out as indicated on each of Figures 14 to 19 (blue prints), it being assumed that this area corresponded to that part of the side of the stack served by the fan chosen. Anemometer readings were then taken at each place marked with a circle.

The anemometer readings were made by timing with a stopwatch the period required by the instrument to indicate 100 feet. The readings were taken at the leaving air side of the stack in all cases, the circulation being reversed when required. While operating the anemometer care was taken to keep as far away as possible in order to reduce the risk of interfering with the air flow in the vicinity of the instrument.

Anemometer readings were also made on the entering air side of the stack of the air being delivered down the side. For this purpose the area between the top of the stack and the wall was assumed divided as shown in Figures 20 to 25 (blue prints), anemometer readings being taken in each position marked with a circle.

RESULTS.

The velocity readings taken at the different positions on the leaving air side of the stack in each different case are shown on the diagrams given in Figures 14 to 19 inclusive Horizontal, vertical and grand averages have been determined and are given on the diagrams.

The results of the tests of the delivery of the air down the sides of the stacks are shown on Figures 20 to 25 inclusive.

A comparison of the total air being circulated by each fan as calculated firstly, by multiplying the average velocity through the stack by the area of the openings, and, secondly, by multiplying the average velocity down the side of the stack by the area between the wall and the stack, is given in the following table :-

TABLE 6.

Distance between wall and stack on entering air side	Air circulated by one fan (cub.ft.per min)	
	Measured on side of stack	Measured between stack and wall of kiln.
12 inches	2820	3480
13 "	3070	3440
15 "	3100	3410
16 "	2950	3520
17 "	3030	3460
20 "	3090	3640

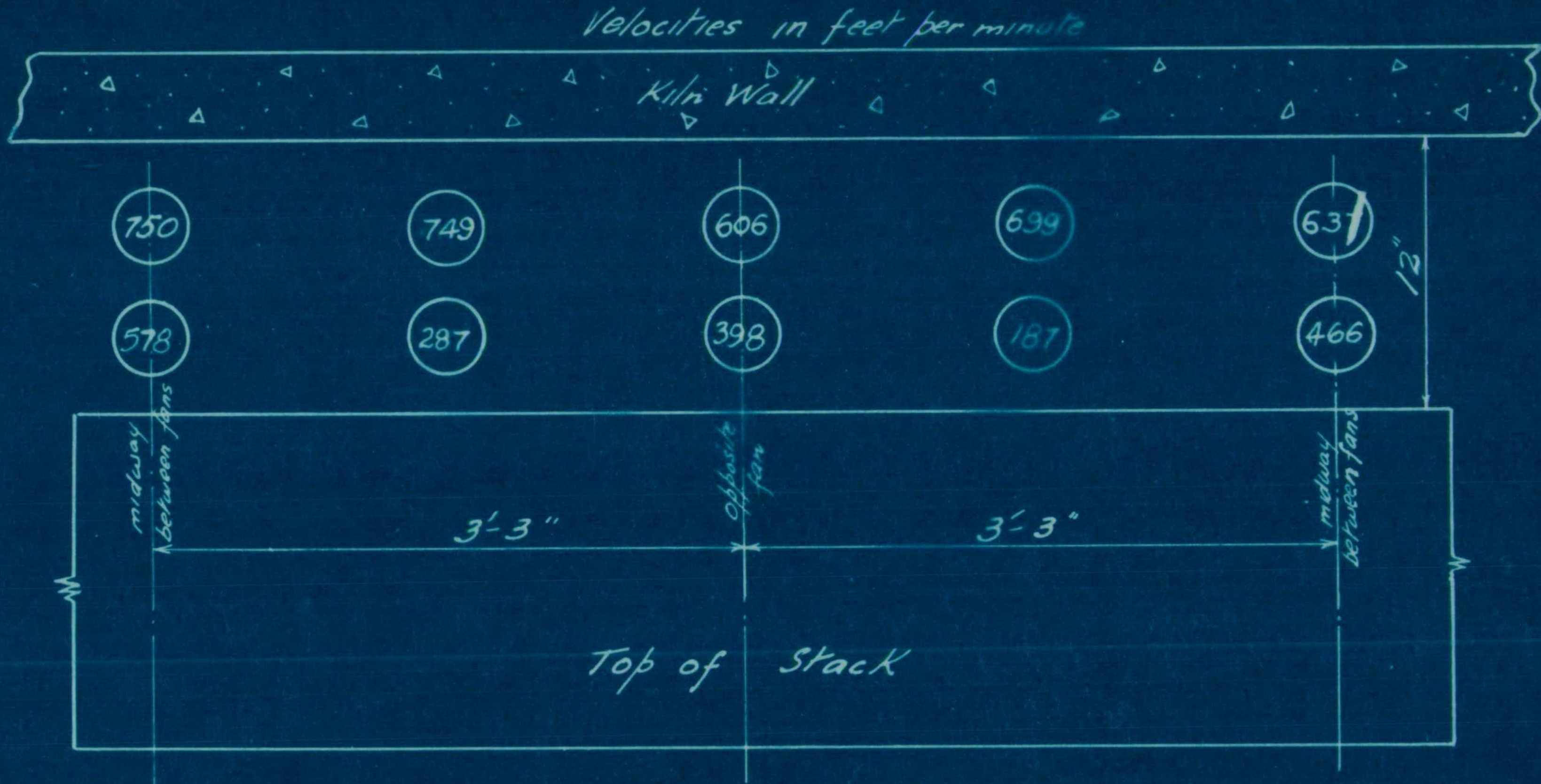


FIG. 20. THE VELOCITY DISTRIBUTION IN THE 12" OPENING BETWEEN STACK & WALL

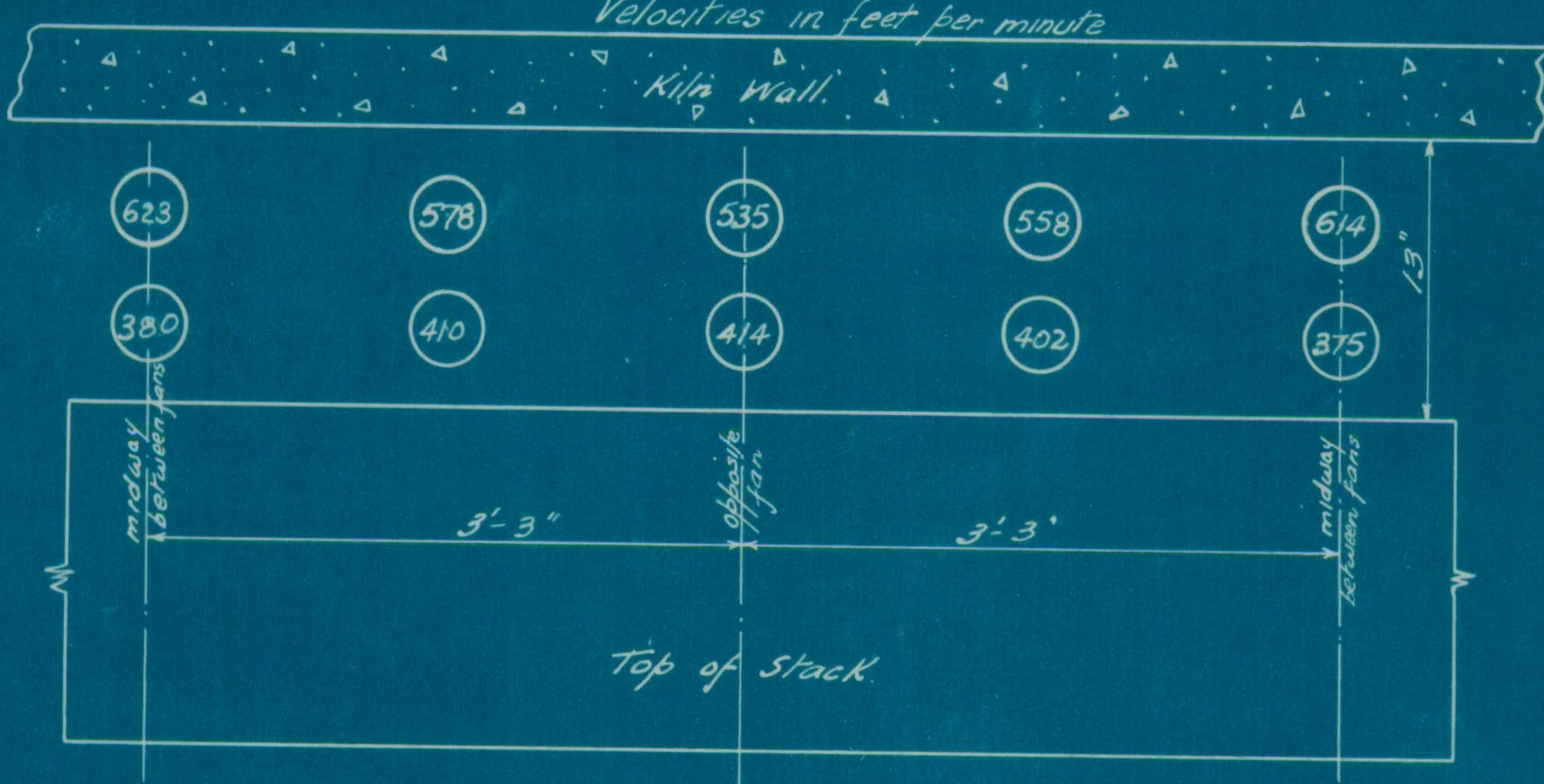


FIG. 21. THE VELOCITY DISTRIBUTION IN THE 13" OPENING BETWEEN STACK & WALL

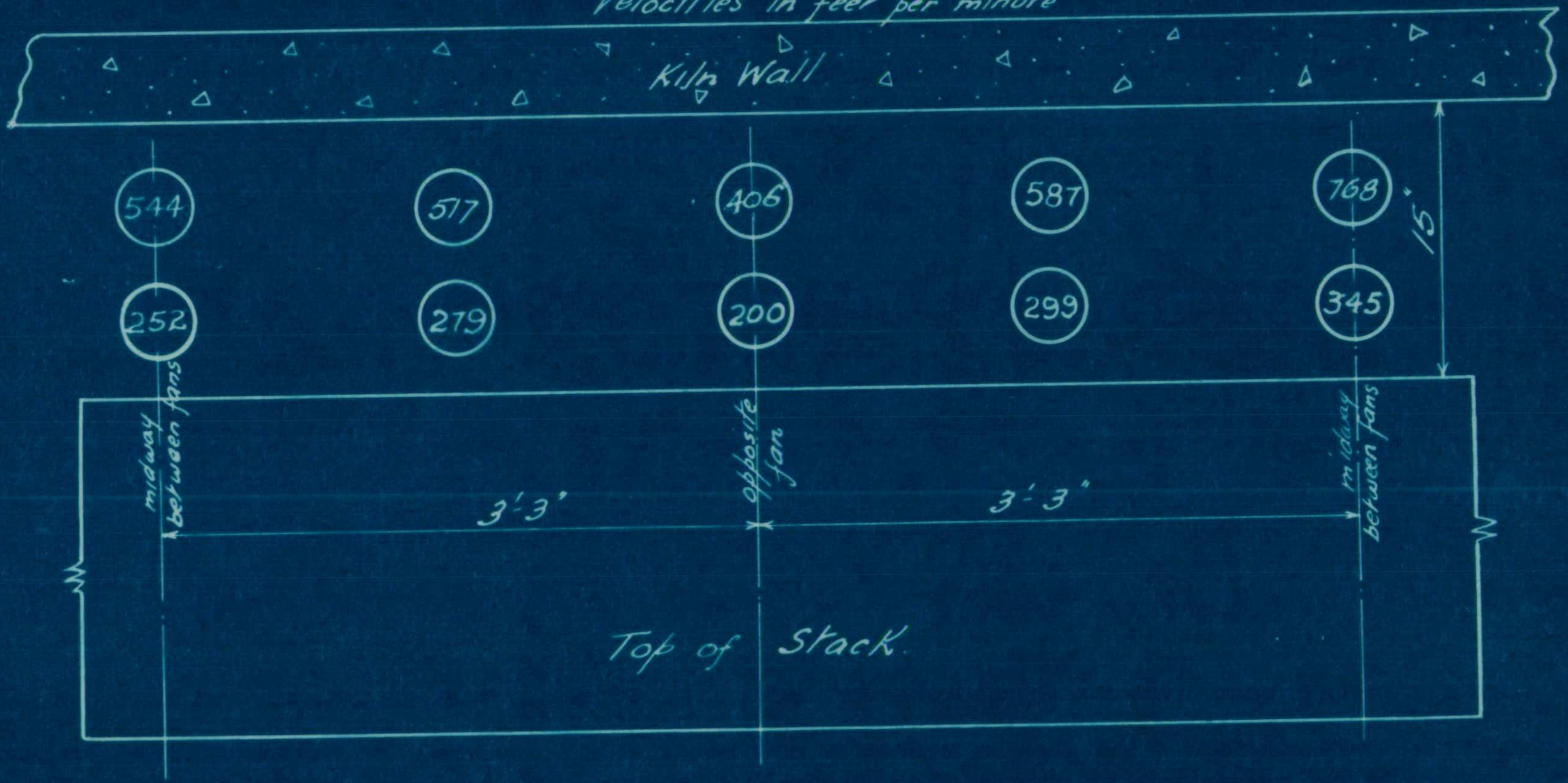


FIG. 22. THE VELOCITY DISTRIBUTION IN THE 15" OPENING BETWEEN STACK & WALL

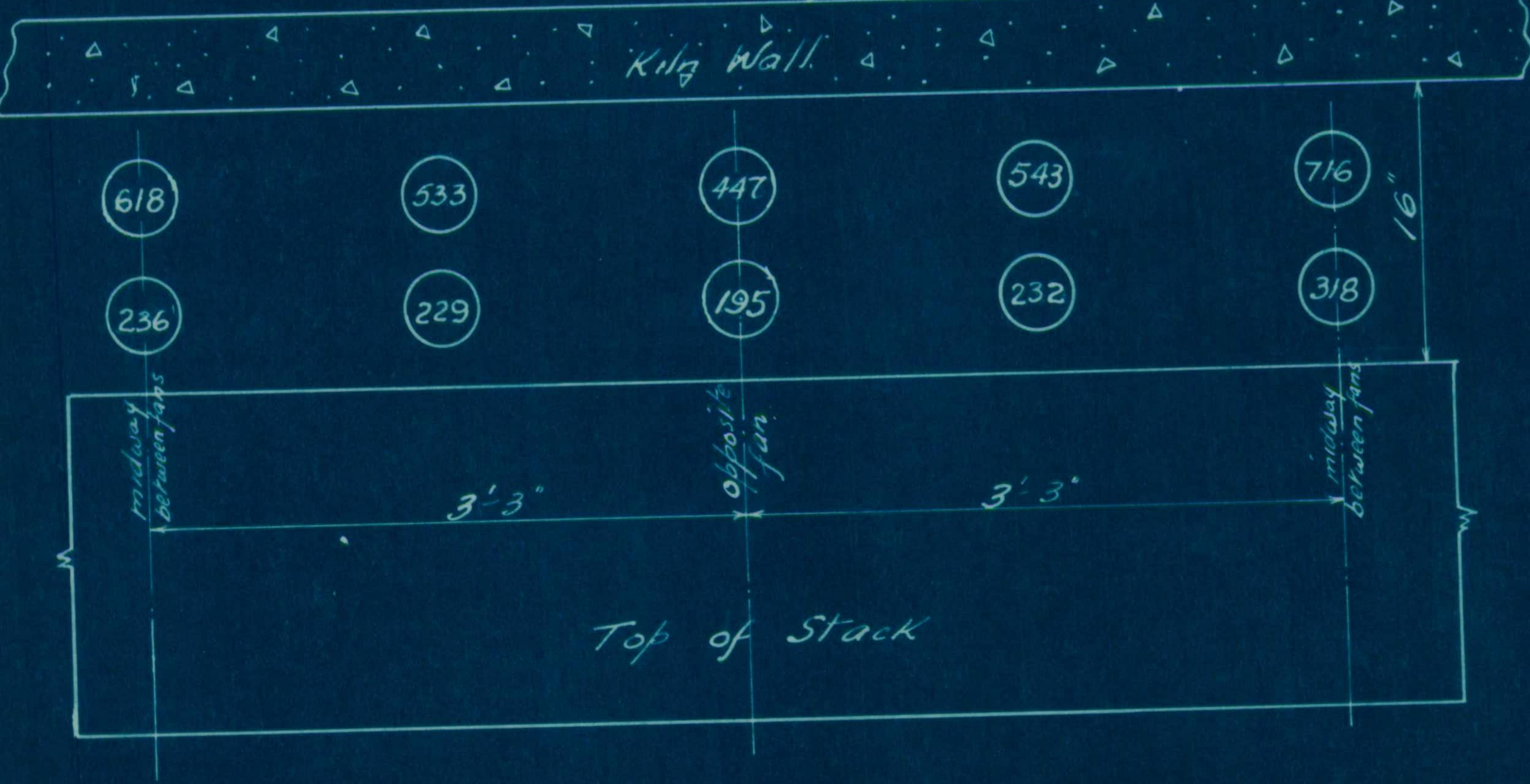


FIG. 23 THE VELOCITY DISTRIBUTION IN THE 16" OPENING BETWEEN STACK & WALL.

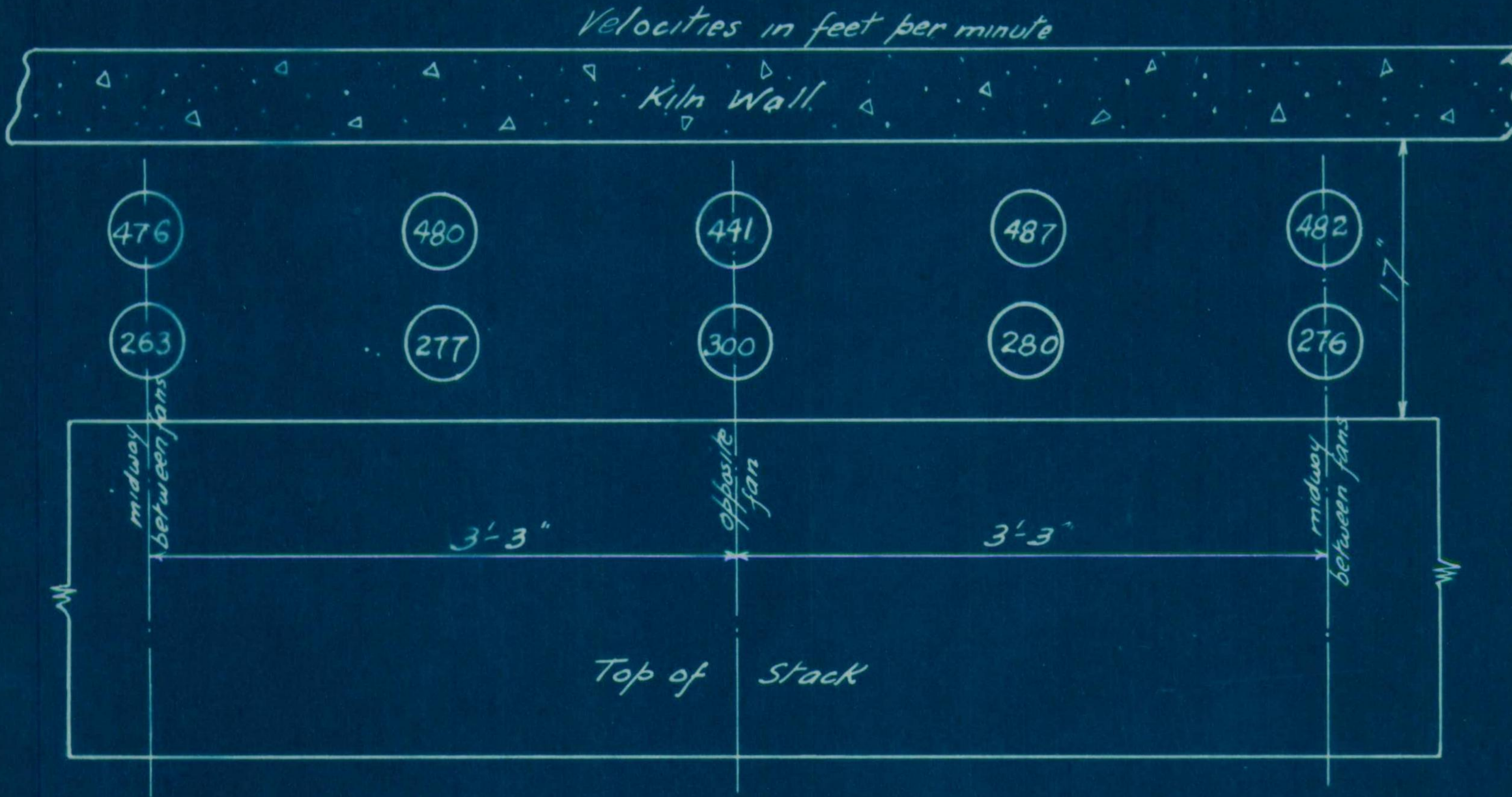


FIG. 24. THE VELOCITY DISTRIBUTION IN THE 17" OPENING BETWEEN STACK & WALL.

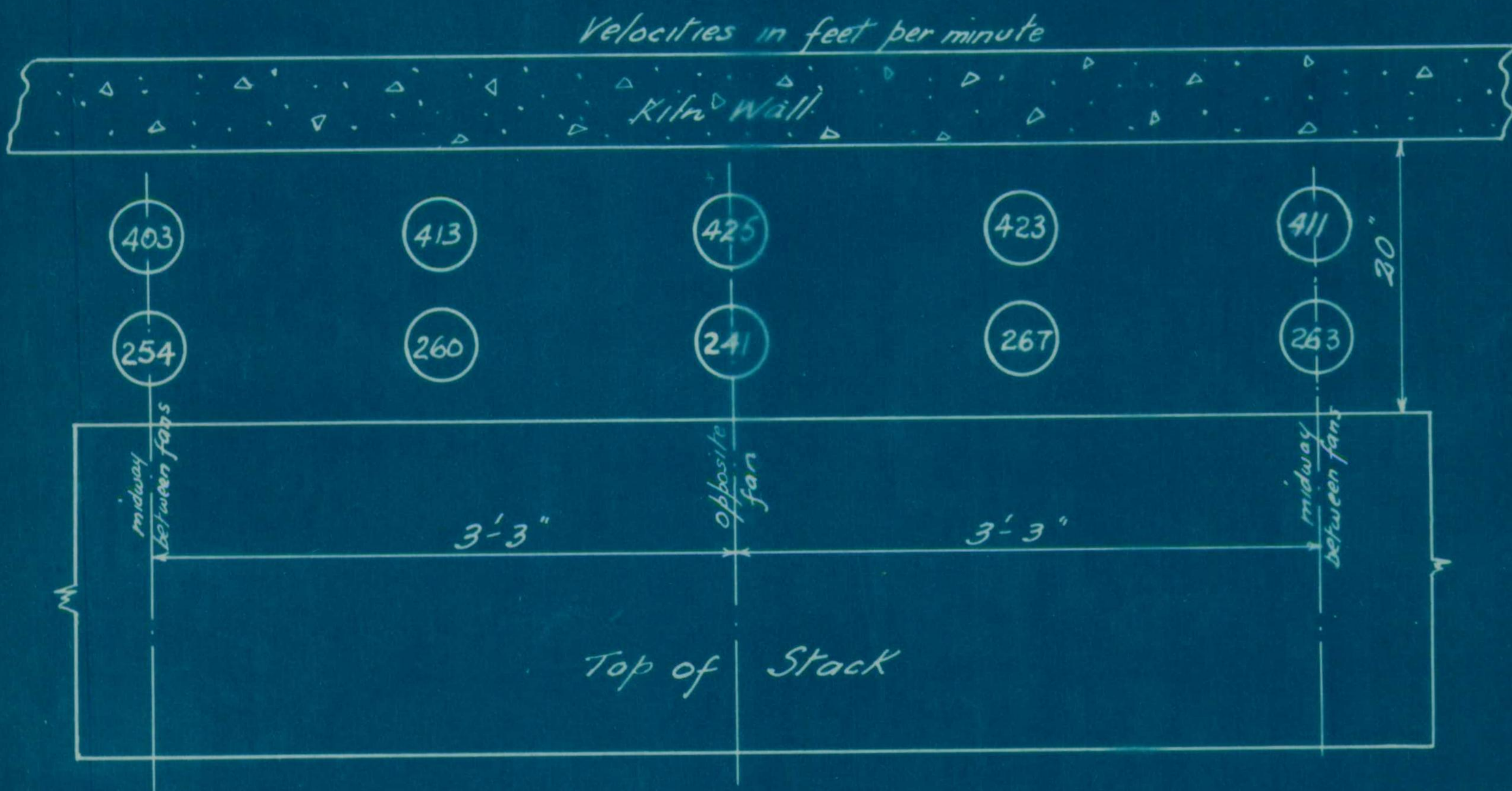


FIG. 25. THE VELOCITY DISTRIBUTION IN THE 20" OPENING BETWEEN STACK & WALL.

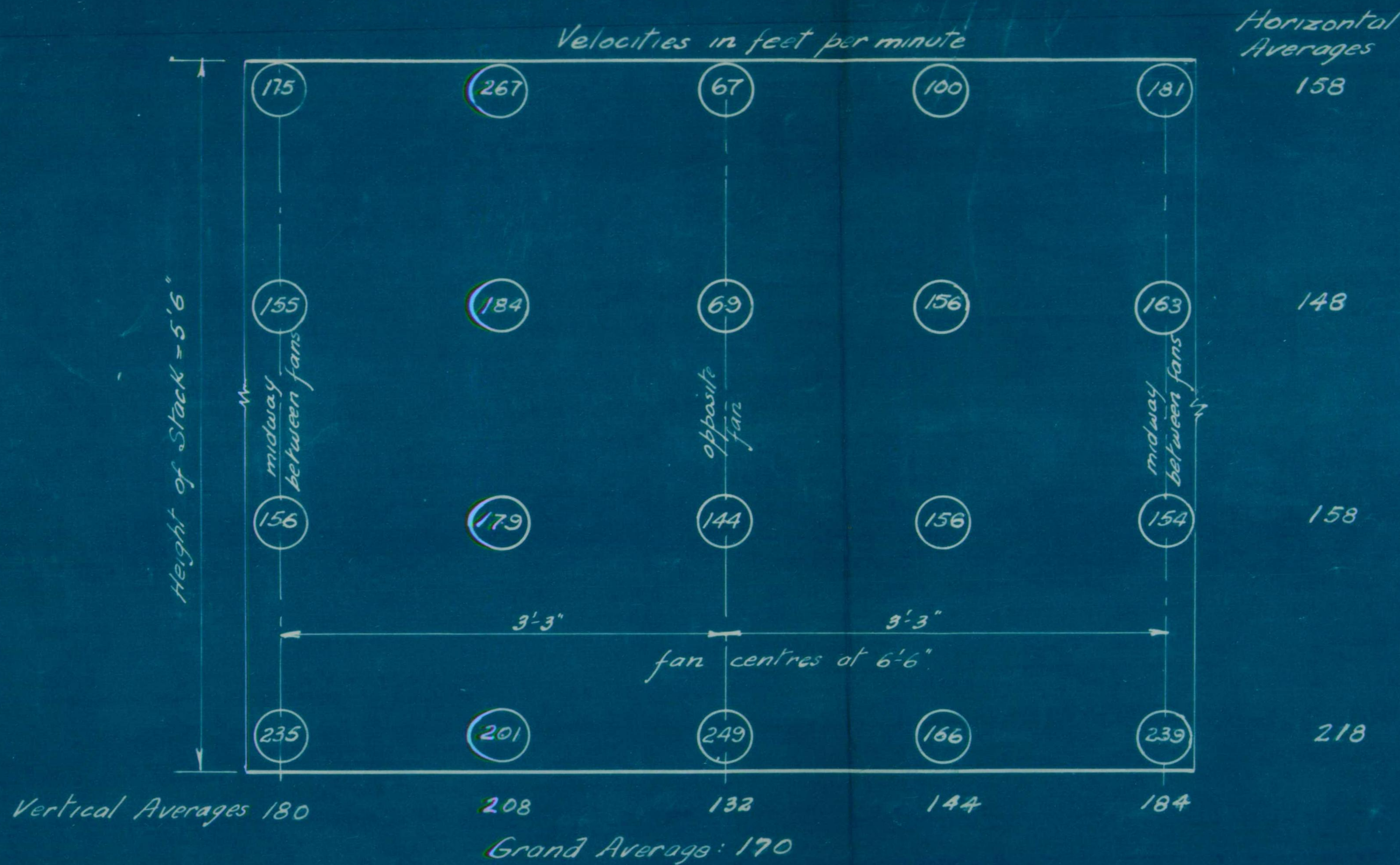


FIG 14. THE VELOCITY DISTRIBUTION OF THE AIR FROM A FAN. SPACE BETWEEN WALL & SIDE OF STACK = 12 INS

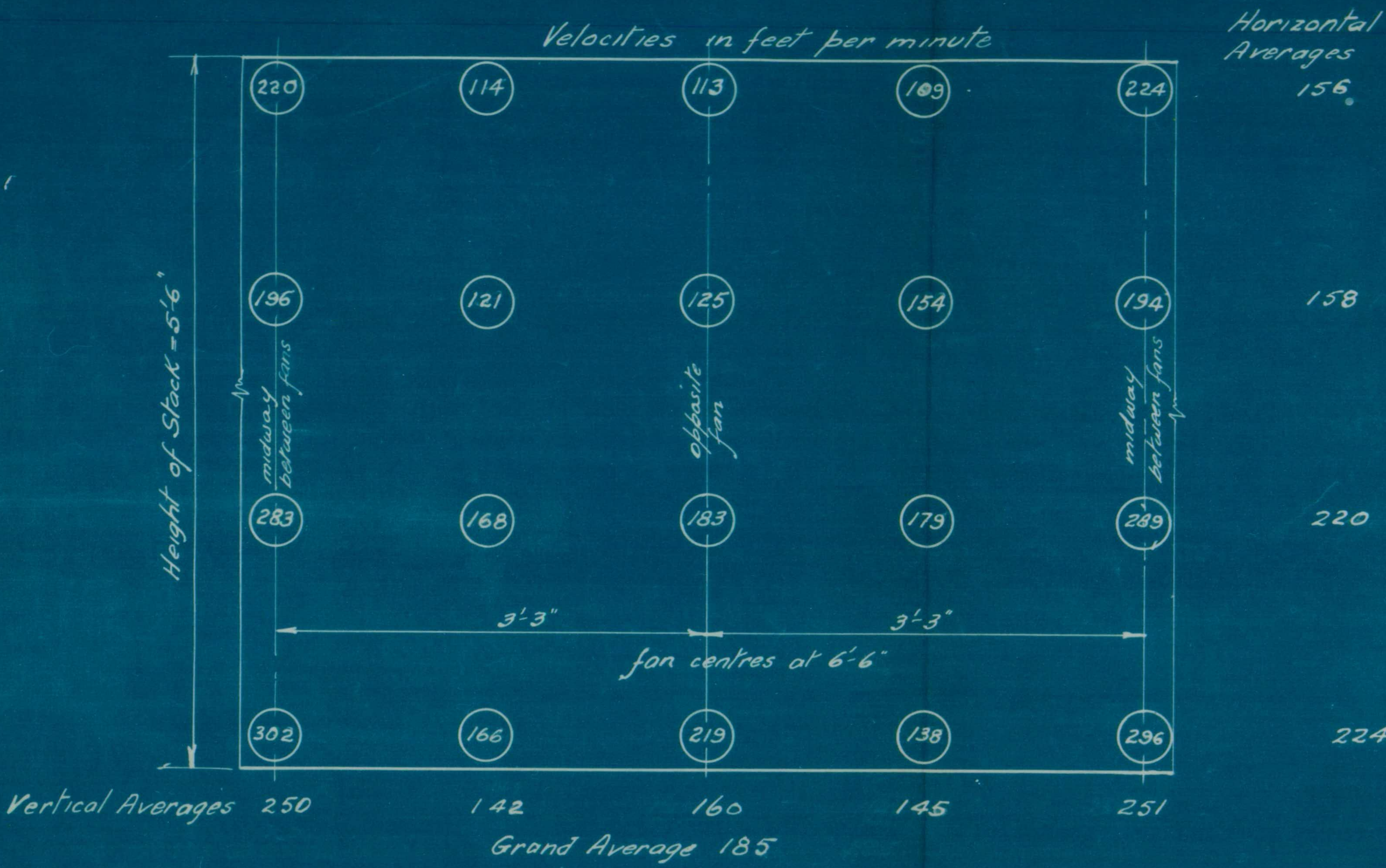


FIG. 15. THE VELOCITY DISTRIBUTION OF THE AIR FROM A FAN. SPACE BETWEEN WALL & SIDE OF STACK = 13 INS

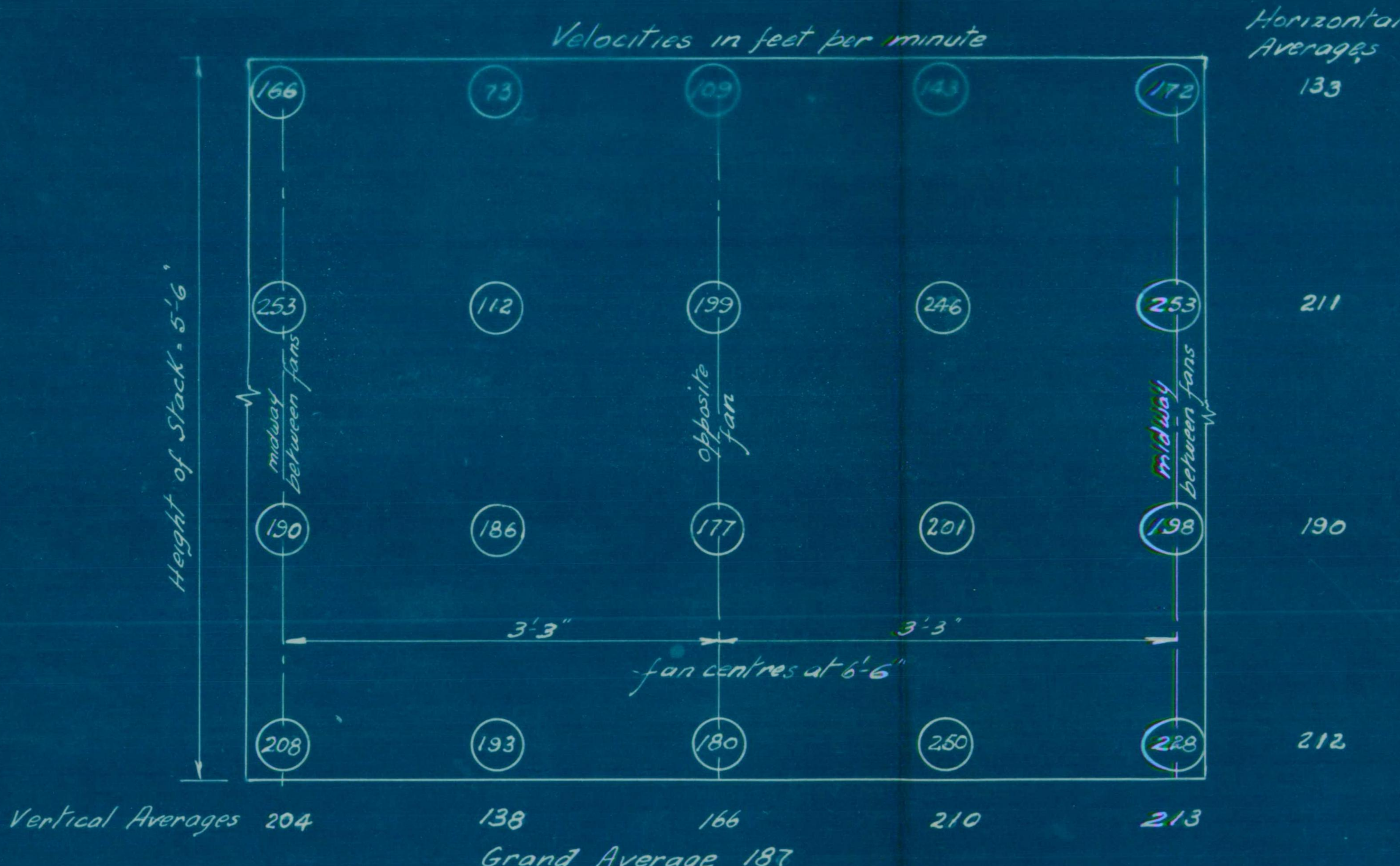


FIG. 16 THE VELOCITY DISTRIBUTION OF THE AIR FROM A FAN. SPACE BETWEEN WALL & SIDE OF STACK = 15 INS.

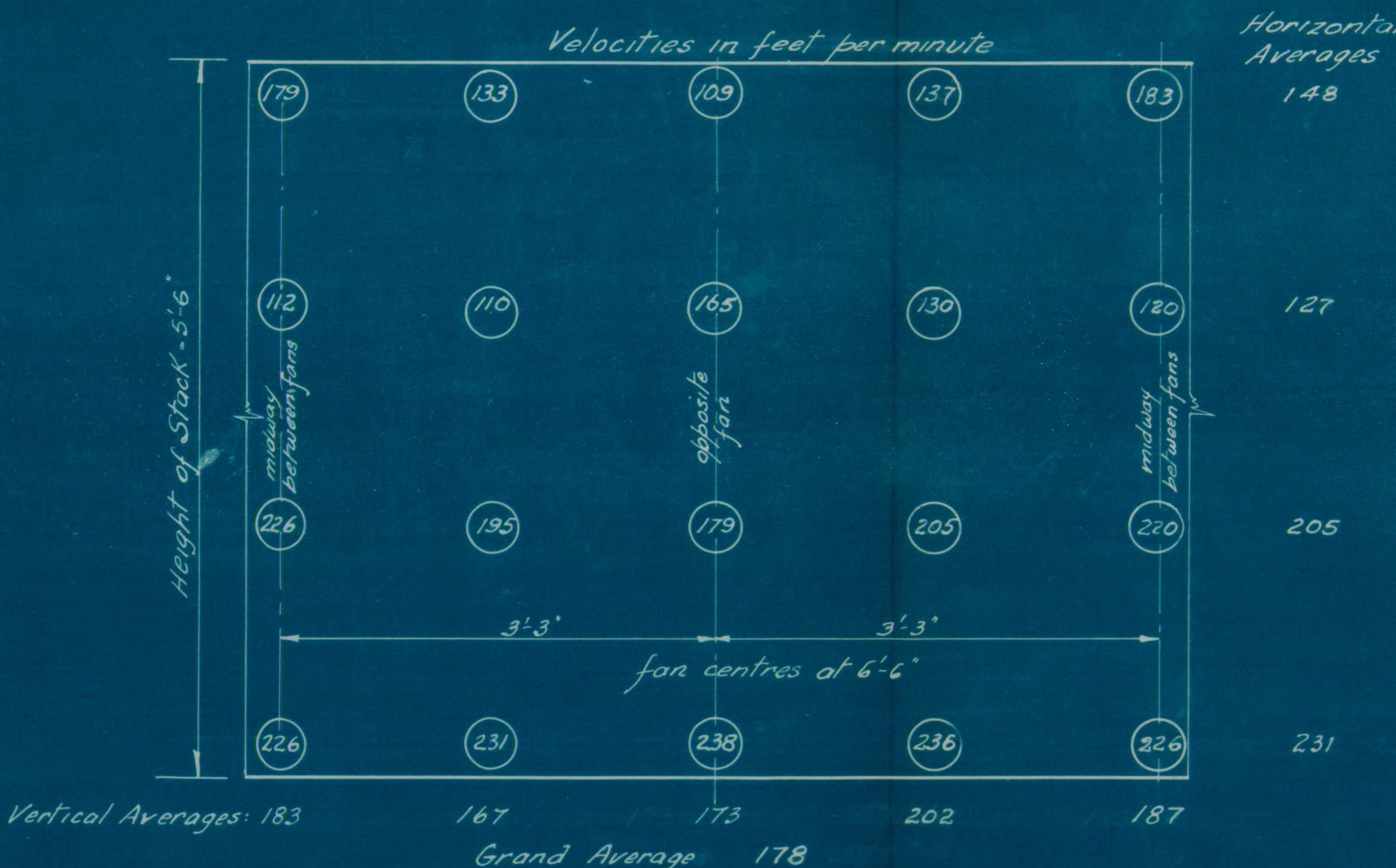


FIG. 17 THE VELOCITY DISTRIBUTION OF THE AIR FROM A FAN. SPACE BETWEEN WALL & SIDE OF STACK = 16 INS

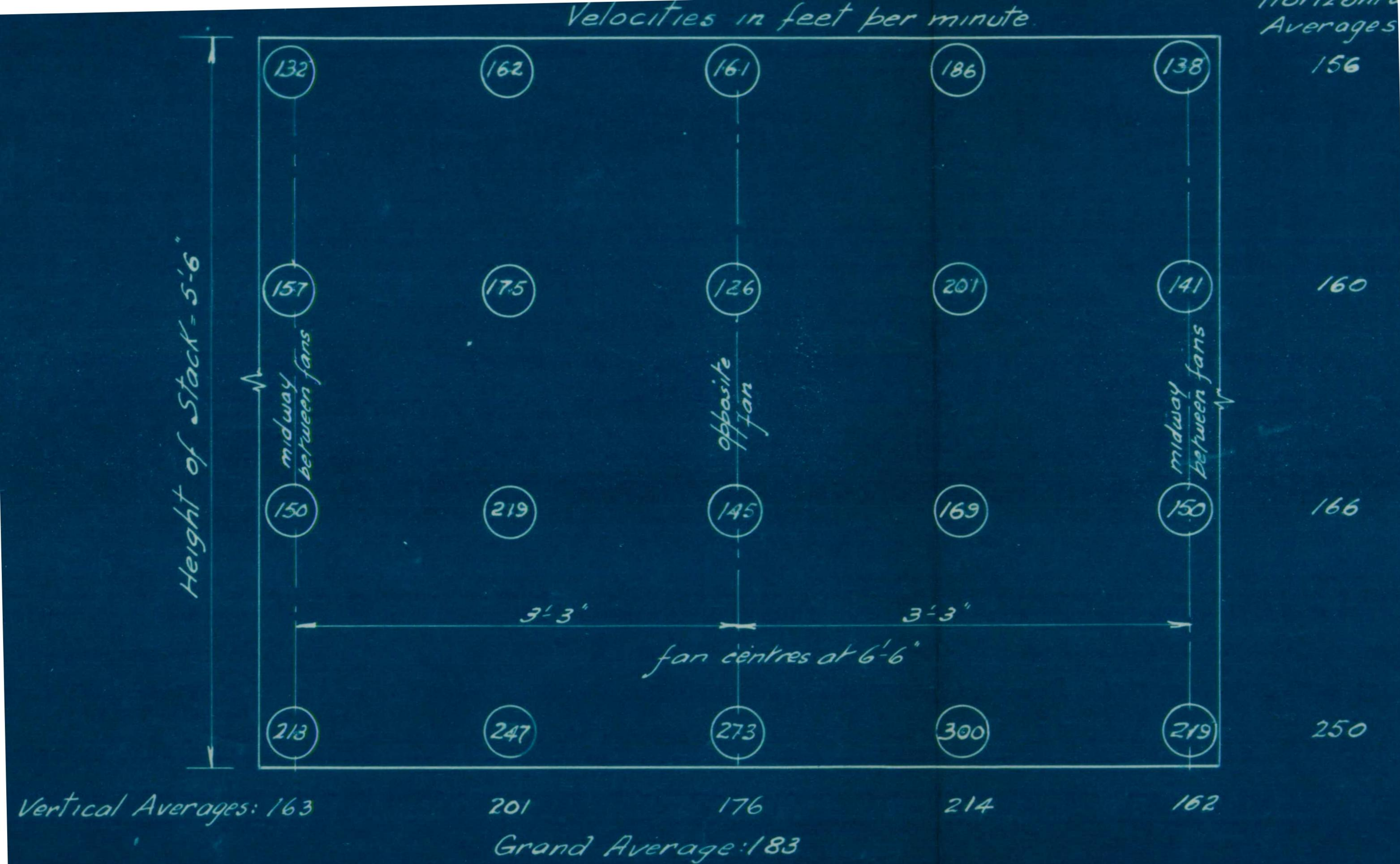


FIG. 18. THE VELOCITY DISTRIBUTION OF THE AIR FROM A FAN. SPACE BETWEEN

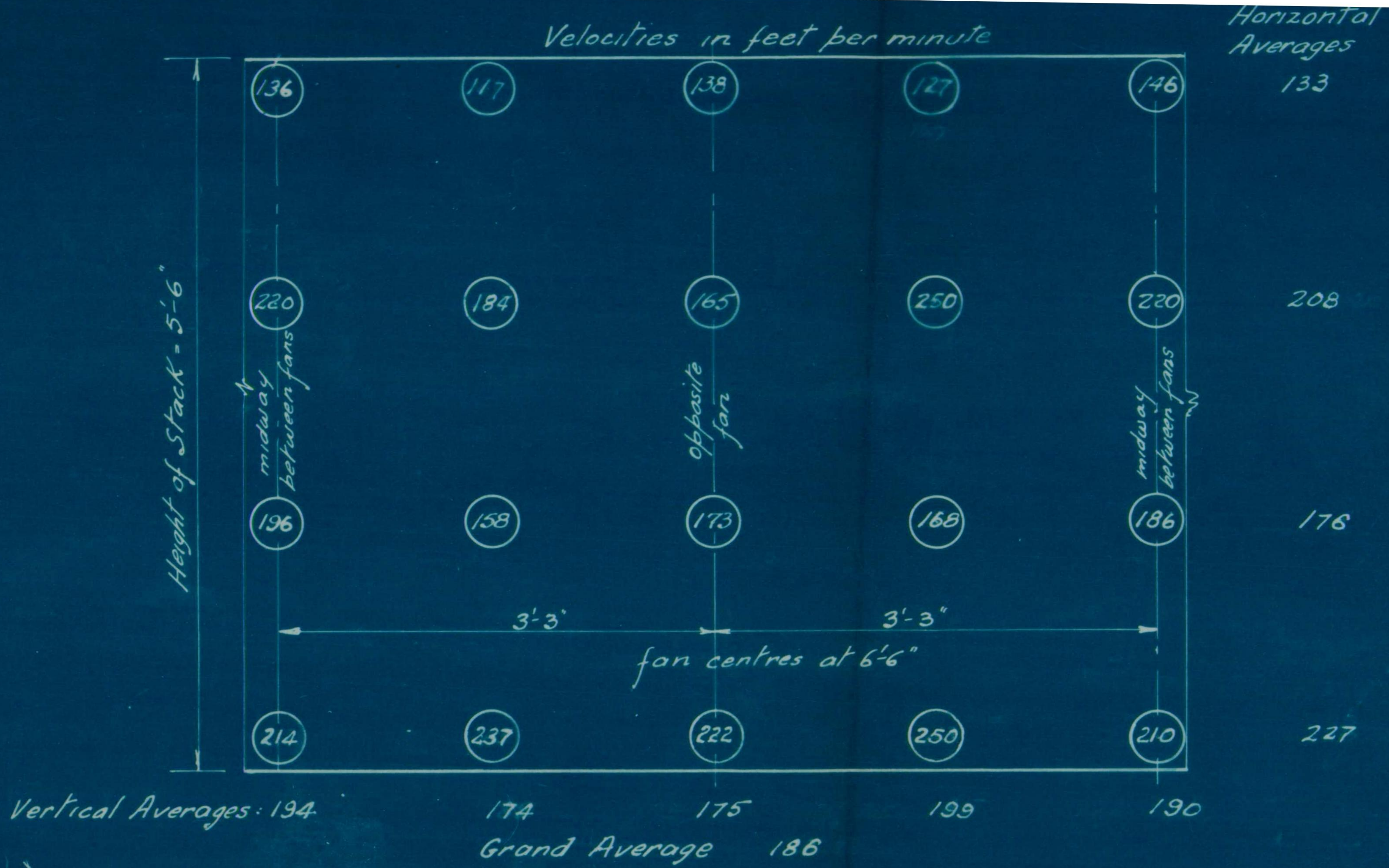


FIG. 19. THE VELOCITY DISTRIBUTION OF THE AIR FROM A FAN. SPACE BETWEEN WALL & SIDE OF STACK = 20 INS.

DISCUSSION OF RESULTS.

The variation in the air distribution over the side of the stack is somewhat irregular, due, probably, to the occasional slight projection of odd boards from the sides. Certain tendencies are quite pronounced, however. In most cases the velocities directly opposite the fans are less than midway between them and the velocities at the tops of the stacks are definitely less than towards the bottoms.

A careful examination of the results shows that of all the cases examined the variation is least with the 20-in. wide space on the entering air side. However, the variation in this case is very little better than for the 15-in, 16-in, or 17-in. wide spaces, and bearing in mind that it is desirable to fill as much of the kiln as is consistent with satisfactory circulation, there seems little justification for changing the previously recommended width of 16-in. The 12-in. and 13-in. spaces appear definitely too narrow.

Even the best distribution found in these tests was not entirely satisfactory. The problem calls for further investigation and it would appear that by far the most satisfactory way of doing this would be by means of an experimental kiln of commercial proportions in cross section and so constructed that its actual dimensions could be readily modified.

An examination of Figures 20 to 25 will show that in the flow of air down the side of the stack the velocity increases from the stack to the wall. The fans are delivering approximately 500 cubic ft. per minute less than their normal rated capacity. They would deliver the 4,000 cubic ft. per minute if speeded up to approximately 600 r.p.m.

The results given in Table 6 indicate that the method of measuring velocities across the stack can be applied to commercial kilns with at least a fair degree of accuracy. The discrepancies between the two sets of figures are due, at least to a considerable extent, to the air leakage through the opening made by the 2-in. bearers at the bottom of the stack. Some of the difference may be due to the air leaving the stack and passing through the anemometer at an angle (see page 12, Experiment 1).

APPENDIX 1.

THE THEORETICAL CALCULATION OF THE QUANTITY OF AIR REQUIRED TO BE CIRCULATED AND THE CHANGE IN DRYING CONDITIONS THROUGH A STACK OF TIMBER.

In the drying of a stack of timber of commercial proportions, the heat necessary for the evaporation of the moisture must be conveyed to the timber by means of the air passing through the stack. It follows that if the temperature and humidity of the air entering the stack are specified, then the temperature or the humidity of the air leaving the stack is pre-determined as well as the amount of moisture which may be evaporated.

If the humidity of the leaving air is to be assumed in order to calculate its temperature, care must be taken that the assumed figure is within the limits imposed by the quantity of vapour per pound of dry air entering the stack.

Since volumes change with changes in pressures and temperatures, one pound of dry air with its accompanying moisture will be considered in the present calculations. The independent pressures of the air and of the vapour will vary according to the relative humidity and the temperature, but it is assumed that the total pressure always remains at atmospheric.

The heat required to evaporate one pound of moisture will be the latent heat of vaporisation, plus the amount necessary to raise the temperature of the water from some initial temperature at which it is placed in the kiln, plus the heat necessary to raise the temperature of the timber containing one pound of moisture. There is also to be considered the heat of adsorption which should be included when drying takes place below the fibre saturation point. In practice the stack of timber is usually heated before appreciable drying begins so that in considerations involving the quantity of air to be circulated, it can be assumed that the timber and the moisture are already heated to the temperature at which evaporation occurs. Furthermore, as the heat of adsorption is very small, this quantity can be neglected. Such a procedure is further justified by the fact that the faster drying rates for which the quantity of air must be provided in most cases occur when the timber is above fibre saturation point.

Let t_1 and t_2 be the entering and leaving temperatures respectively, and h_1 and h_2 the corresponding relative humidities.

Let d_1 and d_2 be the lbs.of water per lb. of dry air entering and leaving respectively.

Let r be the specific heat of air at constant pressure and s that of superheated vapour.

Let H be the heat required to vaporise one pound of moisture from and at t_2

The amount of heat given up by a pound of air in passing through a stack is :-

$$(r + d_1 \times s) \ (t_1 - t_2)$$

The amount of water evaporated is $(d_2 - d_1)$ and the heat required is $H(d_2 - d_1)$. These two equations are equal hence :

$$(r + d_1 \times s) \ (t_1 - t_2) = H(d_2 - d_1)$$

$$\text{or} \quad \frac{H}{r + d_1 \times s} = \frac{t_1 - t_2}{d_2 - d_1} \quad \ldots\ldots\ldots\ldots \quad (1)$$

It can be assumed that the entering air temperature (t_1) and relative humidity (h_1) are known so that d_1 can be determined from tabulated properties of air[5]. To facilitate this determination, the psychrometric chart, Figure 26, has been reproduced. We require to find $d_2 - d_1$, the amount of water evaporated per lb. of dry air. Obviously either the temperature or the relative humidity of the leaving air must first be assumed. If we know t_2 the calculation of d_2 is simple, as all other factors are known or can be determined from tables. The specific heat of air r is 0.2375 and that of super-heated vapour s is 0.475. H varies with t_2 and can be determined from Figure 27 which has been prepared from steam tables[6].

The problem is not quite so simple when the relative humidity of the leaving air is assumed instead of the temperature. In this case, H is known approximately only as it depends on t_2. The relation between t_2 and d_2 is complex and cannot be expressed by any simple equation; it is generally shown by means of a curve (see Figure 26). For short intervals the relation may be taken as a straight line, and the equation obtained from two points close together may be used for the local calculation. The straight line equation may then be introduced into (1). H may as a first approximation be taken as at t_1 and the equation solved for t_2. The more nearly exact value of H at t_2 may then be substituted and the equation again solved for t_2. From this value of t_2 the

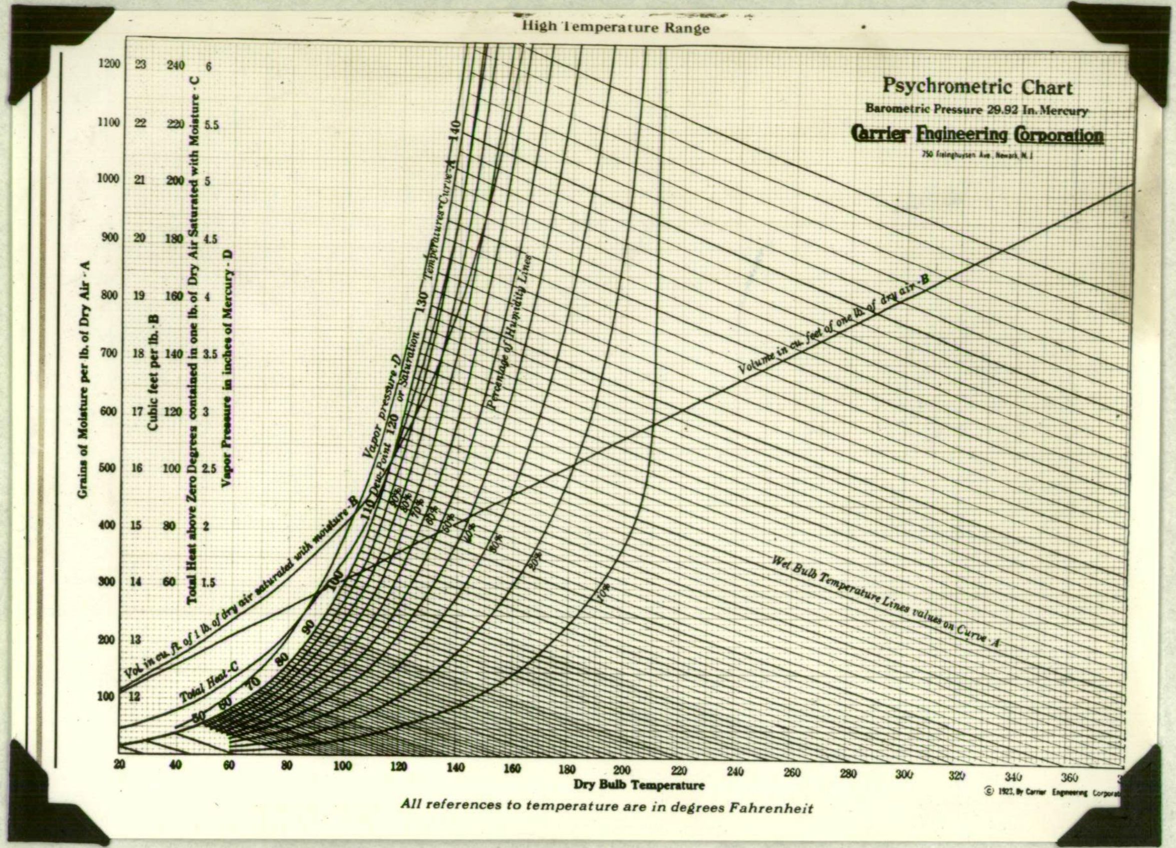


FIGURE 26.

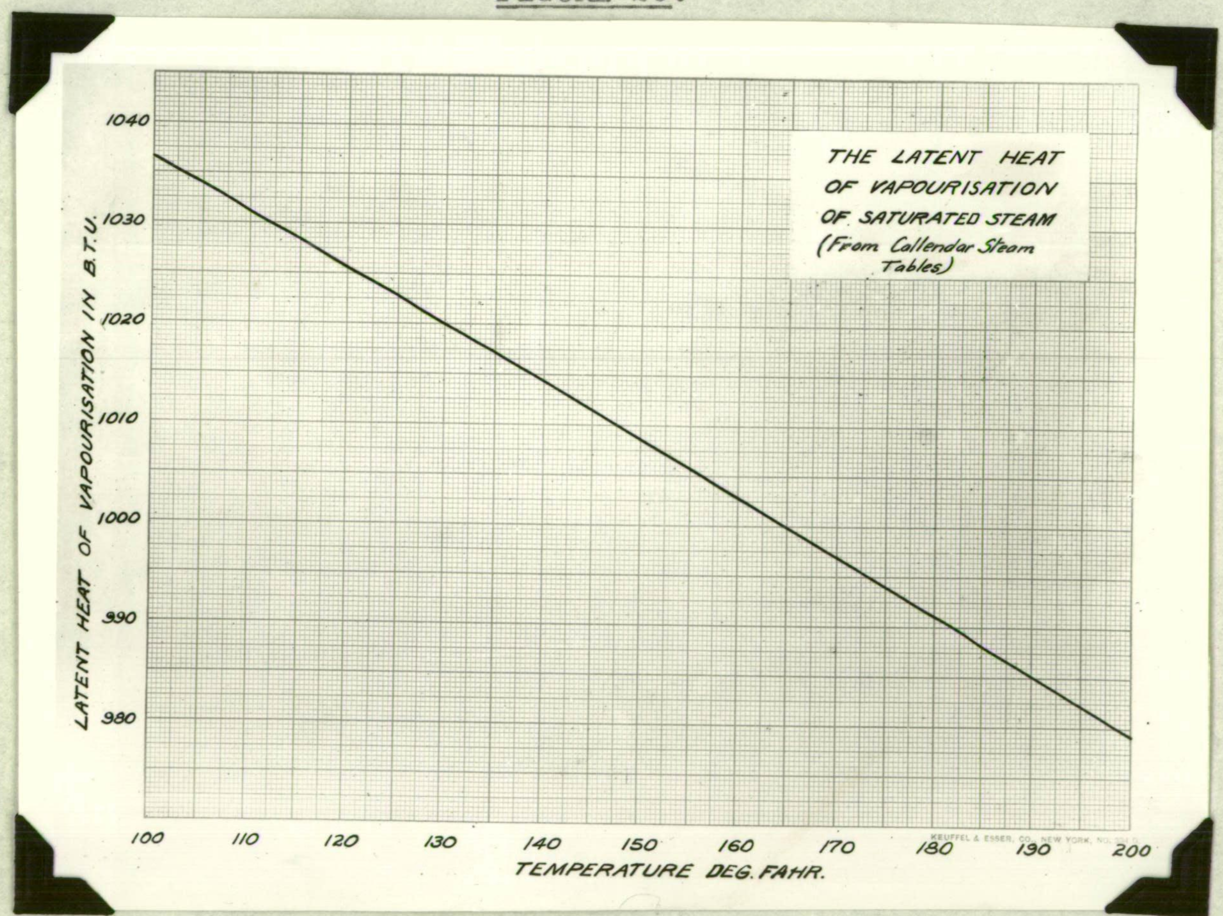


FIGURE 27.

straight line equation derived from the curve may be used to find d_2.

The quantity of dry air by weight to evaporate 1-lb. of moisture is $\frac{1}{d_2 - d_1}$ pounds. The volume occupied by this weight of dry air can be obtained from Figure 26, thus :- Determine the dew-point, i.e. the temperature (t_{dp}) to which the air must be cooled before it becomes saturated. From the same chart the volume occupied by 1-lb. of air when saturated at this temperature can be read off. Let this be V_{dp}. Then :

$$V_{dp} \times \frac{1}{d_2 - d_1}$$

gives the cubic ft. of air required at t_{dp} to evaporate 1-lb. of moisture. But the volume is required at t_1, the temperature of the air entering the stack. The volume will vary directly as the absolute temperature, so that the volume at t_1 is :

$$V_1 = V_{dp} \frac{459.4 + t_1}{459.4 + t_{dp}} \times \frac{1}{d_2 - d_1} \quad \ldots\ldots \quad (2)$$

This gives the volume of air, with its moisture, required to evaporate 1-lb. of moisture.

The quantity of moisture to be evaporated in unit time must next be determined. Let m be the moisture content per cent. (based on oven dry weight of wood) by which the timber is dried in unit time. Let W_{od} be the oven dry weight of 1 cub.ft. of wood. Then $m \times W_{od}$ is the weight of moisture to be evaporated per unit time from 1 cub.ft. of wood.

Let the timber in the stack be t units thick, the width of the stack w, and the thickness of the separating strips s. Let the number of layers and openings be n. Consider a piece of the stack of unit dimensions lengthwise. The volume of timber $= t \times w \times n$.

Weight of moisture to be removed per unit time $= t \times w \times m \times n \times W_{od}$

Volume of air required $= t \times w \times m \times V_1 \times n \times W_{od}$ . . . . . (3)

$$\text{Velocity of air} = \frac{\text{Volume}}{\text{opening area}} = \frac{t \times w \times m \times V_1 \times n \times W_{od}}{s \times n}$$

$$= \frac{t \times w \times m \times V_1 \times W_{od}}{s} \quad . . . (4)$$

Two actual examples, drawn from the experimental work described in Experiment 3, may serve to illustrate the calculations. In the first of these the temperature is given and in the second the leaving air relative humidity.

Example 1. - The entering air temperature and relative humidity are respectively 140°F. and 54 per cent.; the leaving air temperature is 132°F. The timber is 1-in. thick and its oven dry weight per cub.ft. is 34 lb. The strips are 1-in. thick and the stack is 5-ft. wide. What air velocity will be necessary to dry the timber at the rate of 1.39 per cent. moisture content per hour ?

Now eq.(1) is $\dfrac{H}{r + d_1 \times s} = \dfrac{t_1 - t_2}{d_2 - d_1}$

The weight of moisture in 1-lb. of dry air at 140°F. and saturated is (from chart) 1105 grains = .158-lb., and at 54 per cent.relative humidity is $\dfrac{158 \times 54}{100} = .0853 = d_1$

H (at 132°F.) = 1019.

Therefore substituting in equation

$$\frac{1019}{.2375 + 0.0853 \times .475} = \frac{140 - 132}{d_2 - .0853}$$

whence d_2 = .0876 and the rel.hum. of leaving air = $\frac{.0876}{.122}$ = 72%

and $d_2 - d_1$ = .0023

and $\frac{1}{.0023}$ pounds of dry air are required to evaporate 1-lb. of water

The dew point of air at 140°F. and 54 per cent. relative humidity is 119½°F. and 1-lb. of air when saturated at 119½°F occupies 16.45 cub.ft. The volume of the mixture of air and vapour at 140°F. is :

$$16.45 \times \frac{459.4 + 140}{459.4 + 119\frac{1}{2}} = 17.03$$

∴ volume of air required at 140°F. and 54 per cent. relative humidity to evaporate 1-lb. of moisture = $\frac{1}{.0023} \times 17.03 = 7410$.

From equation (4) the velocity of the air is $\frac{t \times w \times m \times V_1 \times W_{od}}{s}$

$$= \frac{\frac{1}{12} \times 5 \times 1.39 \times 7410 \times 34}{60 \times \frac{1}{12}}$$

= 292 feet per minute.

<u>Example 2</u>. - Assume the same conditions as in Example 1, but instead of the leaving air temperature being given, the leaving are relative humidity is given as 72 per cent.

Substituting as before (but taking H at 140 as t_2 is not known).

$$\frac{1014\frac{1}{2}}{.2375 + .0853 \times .475} = \frac{140 - t_2}{d_2 - .0853}$$

or $$\frac{140 - t_2}{d_2 - .0853} = 3650 \quad \ldots\ldots\ldots\ldots (5)$$

To obtain the relation between t_2 and d_2 take two sets of values for lb. of vapour accompanying 1-lb. of air at 72 per cent. relative humidity near the expected value of t_2 and assume a straight line relation. Thus :

$$d = a + bt.$$

when t is 135, d = .0961. when t is 130, d = .0824.

$$\text{then } \begin{array}{rcl} .0961 & = & a + 135b \\ .0824 & = & a + 130b \end{array} \Bigg)$$

$$\text{subtracting, } \begin{array}{rcl} .0137 & = & 5b \\ b & = & .00274. \end{array}$$

substituting for b in the first equation,

$$\begin{array}{rcl} .0961 & = & a + .3695 \\ a & = & -.2734. \end{array}$$

whence $d_2 = -.2734 + .00274t_2$

Substituting for d_2 in eq.(5)

$$\frac{140 - t_2}{-.2734 + .00274t_2 - .0853} = 3650.$$

Whence $t_2 = 132^oF.$

But the value of H was taken at 140°F. instead of at 132°F.

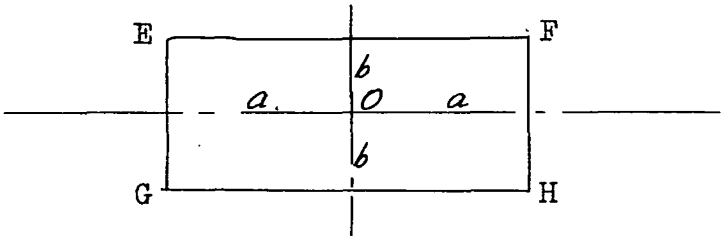
Re-substituting the new value of H, and solving again,

$$\frac{1019}{.2375 + .0853 \times .475} = \frac{140 - 132}{d_2 - .0853}$$

whence d_2 = .0876 and the calculation proceeds as in Example 1.

APPENDIX 2.

THEORETICAL FORMULA FOR STREAM LINE FLOW IN RECTANGULAR DUCT.



Let E F G H represent a cross section of the rectangular duct. Take the origin of co-ordinates at the centre of the cross section, Ox parallel to the longer side, Oy parallel to the shorter side, and Oz parallel to the axis of the pipe. w is the velocity in the direction Oz.

The general equations of motion (see Gibson[4] page56), reduce to -

$$\frac{\partial p}{\partial x} = 0, \qquad \frac{\partial p}{\partial y} = 0, \qquad \frac{\partial p}{\partial z} = \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) \quad \ldots\ldots\ldots \quad (1)$$

The first two equations show that the pressure is constant over the section.

Let $T = -\frac{1}{2\mu} \cdot \frac{\partial p}{\partial z}$ and $w = S + T(b^2 + y^2)$.

Substituting in (1) we have -

$$\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

The object of introducing S is to simplify the boundary conditions. Along the boundary

$$S + T(b^2 - y^2) = w = 0 \quad \ldots\ldots\ldots\ldots \quad (3)$$

Hence along EF, GH -

$$S = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

and along EG, FH

$$S = -T(b^2 - y^2) \dots \dots \dots \dots \dots (5)$$

From (4) all terms in S must vanish when $y = \pm b$. This condition is satisfied by terms such as -

$$\eta \cos \frac{(2n+1)\pi y}{2b}$$

where η is a function of x only and n is any integer

substitute $S = \eta \cos my$ in (2) then

$$\frac{\partial S^2}{\partial x^2} - m^2 \eta = 0 \dots \dots \dots \dots \dots (6)$$

whence

$$\eta = A_n \cosh mx + B_n \sinh mx \dots \dots \dots \dots (7)$$

By symmetry about Oy, $B_n = 0$, hence

$$\eta = A_n \cosh mx \dots \dots \dots \dots \dots (8)$$

and S consists of terms like

$A_n \cosh mx \cos my$, where

$m = (2n+1)\pi/2b.$

These terms must now be made to satisfy the other boundary condition (eq.5).

For convenience let $y = \frac{2b\,\theta}{\pi} \dots \dots \dots \dots (9)$

Then $S = \sum_{n=0}^{n=\infty} A_n \cosh \frac{(2n+1)\pi x}{2b} \cdot \cos (2n+1)\theta \quad \dots (10)$

Substituting from (9) in (5) we have

$$S = T.4b^2 \left(\theta^2 - \tfrac{1}{4}\pi^2\right)/\pi^2 \dots \dots \dots \dots (11)$$

This must agree with (10) when

$x = \pm a$, i.e. with

$$S = \sum_{n=0}^{n=\infty} A_n \cosh \frac{(2n+1)\pi a}{2b} \cdot \cos (2n \quad 1)\theta \quad \dots (12)$$

Expending (11) in a Fourier's series we have

$$S = -\frac{32T\ b^2}{\pi^3}\left\{\cos\theta - \frac{1}{3^3}\cos 3\theta + \frac{1}{5^3}\cos 5\theta \ldots\right\} \quad \ldots (13$$

Comparing co-efficients in (12) and (13) we obtain A_0, A_1, etc.

whence we find -

$$S = -\frac{32T\ b^2}{\pi^3}\left\{\frac{\cosh(\pi x/2b)}{\cosh(\pi a/2b)}\cos\frac{\pi y}{2b} - \frac{1}{3^3}\frac{\cosh(3\pi x/2b)}{\cosh(3\pi a/2b)}\cos\frac{3\pi y}{2b} + \ldots\ldots\ldots\ldots\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Hence

$$w = -\frac{32T\ b^2}{\pi^3}\left\{\frac{\cosh(\pi x/2b)}{\cosh(\pi a/2b)}\cos\frac{\pi y}{2b} - \frac{1}{3^3}\frac{\cosh(3\pi x/2b)}{\cosh(3\pi a/2b)}\cos\frac{3\pi y}{2b} + \ldots\right\} + T(b^2 - y^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

The total flow is given by

$$Q = \int_{y=-b}^{y=+b}\int_{x=-a}^{x=+a} w\,dx\,dy \quad \ldots\ldots\ldots\ldots (16)$$

The integration of the terms in (15) is a straightforward matter and gives finally -

$$Q = -\frac{4}{3}\cdot\frac{ab^3}{\mu}\cdot\frac{dp}{dz}\left\{1 - \frac{192}{\pi^5}\cdot\frac{b}{a}\left(\tanh\frac{\pi a}{2b} + \frac{1}{3^5}\tanh\frac{3\pi a}{2b}\ \ldots\right)\right\} \ldots (17)$$

If v is the mean velocity flow in the duct -

$$v = \frac{Q}{4ab}$$
$$= \frac{Cb^2}{3\mu}\cdot\frac{dp}{dz} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

where $C = \left\{1 - \frac{192}{\pi^5}\cdot\frac{b}{a}\left(\tanh\frac{\pi a}{2b} + \frac{1}{3^5}\tanh\frac{3\pi a}{2b} + \ldots\right)\right\}$

when $a = \infty$, or the flow is between parallel plates of infinite width

$C = 1$ and

$$v = \frac{b^2}{3\mu}\cdot\frac{dp}{dz} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

ACKNOWLEDGEMENT.

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