AN EXPERIMENTAL INVESTIGATION OF THE MINIMUM REYNOLDS' NUMBER FOR INSTABILITY IN WATER JETS

by

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SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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Signature of Author Signature redacted
Dept. of Aeronautical Engineering, May 21, 1960

Certified by Signature redacted
Thesis Supervisor

Accepted by ______________________
Chairman, Departmental Committee on Thesis

Cambridge, Massachusetts
May 21, 1960

Secretary of the Institute,
Massachusetts Institute of Technology,
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of Bachelor of Science in Aeronautical Engineering, this thesis, entitled, " An Experimental investigation of the minimum Reynolds number for instability in water jets", is submitted.

Respectfully Yours,

Signature redacted

Andrus Viilu

ACKNOWLEDGEMENTS

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ABSTRACT

The laminar-turbulent transition in a cylindrical jet of water was found, experimentally, to occur at a Reynolds' number between 10 and 11. The transition Reynolds' number was not affected by a change in the jet diameter within a factor of three and a change in viscosity of 25%.

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INTRODUCTION

The hydrodynamic stability of two dimensional jets in a viscous incompressible fluid has been the object of much theoetical discussion.

The majority of papers in connection with this problem deal with various ingenious and complicated mathematical methods for the solution of the Orr-Sommerfeld stability equation.

The solutions are not always based on firm physical grounds and in general have to sacrifice physical relavence for mathematical simplicity. For instance a common assumption is that the flow does not diverge with distance from the jet origin. The actual jet, according to Bickley however spreads out as a 2/3 power of this distance.

With this parallel jet assumption and the additional ones of infinite boundaries, and a certain velocity distribution across the jet, an approximate solution has been derived by many authors. The neutral stability curve is generally agreed to be "C" shaped on a wave number vs. Reynolds number plot and the minimun critical Reynolds number is found to be between 4 and 5.5 and occur at a wave number of about .2. The most recent derivation being by L. N. Howard.

While such curves have no exact physical correspondence, it is probably true that they approximate the result to be obtained by experiment.

As it happens, there is very little experimental data available in connection with this problem and consequently not much is really known about the applicability of the theory. The thesis undertaken here is an attempt to fill some of this void of experimental data.

THEORETICAL BASIS

The theoritical calculation for the neutral stability curve of a cylindrically symmetrical free jet in a viscous incompressible fluid can be derrived as follows.

The method here is the one developed by Howard although, as stated privously, other approaches give about the same results.

If one neglects the non-linear terms in the Navier-Stokes equation and introduces Squire's perturbation function one gets the following fourth order differential equation, known as the Orr-Sommerfeld equation.

$$(D^2 - \alpha^2)^2 \phi = i \alpha R \left[(w - c)(D^2 - \alpha^2)\phi - w'' \phi \right]$$

$D = \frac{d}{dy}$ $\quad w = \operatorname{sech}^2 y \quad$ R - Reynolds' number

α - Wave number of instability

c - Complex wave speed

y - Dimensionless distance perpendicular to the stream

ϕ - The y- dependence of the complex perturbation stream function

Squire's perturbation function is given as $\Psi = \phi(y) e^{-i\alpha(x-ct)}$

At this point it can be seen that by taking just the non-viscous equation or setting $\frac{1}{R} = 0$ one gets two limiting solutions.

$$(w - c)(D^2 - \alpha^2)\phi - w''\phi = 0$$

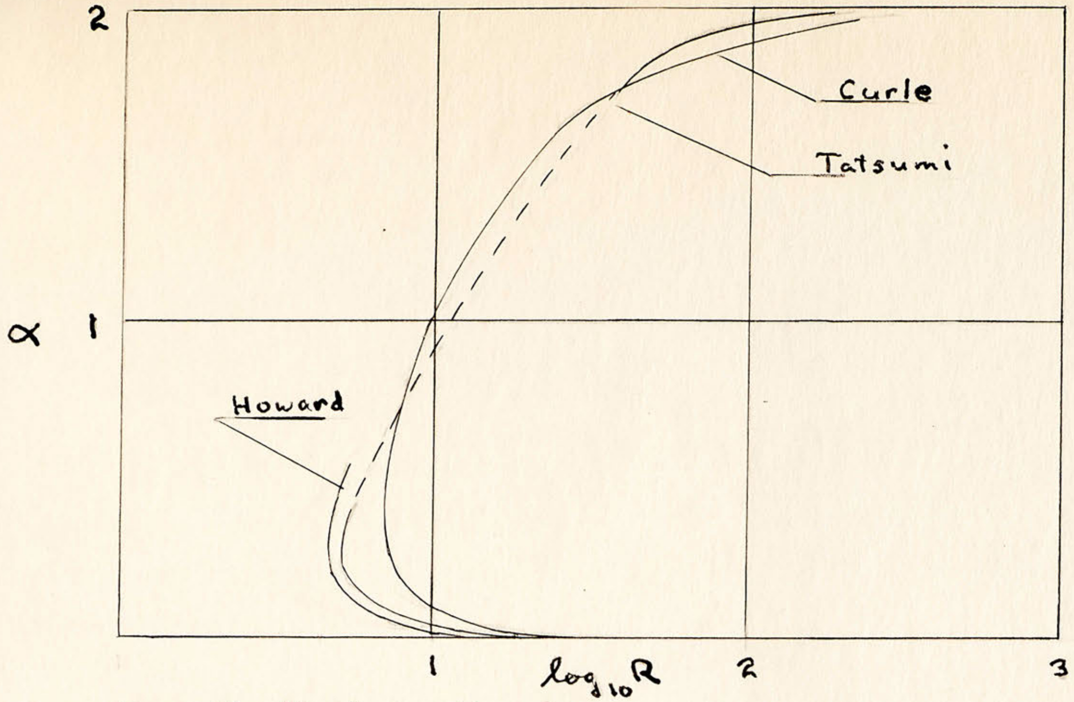
as $R \to \infty$ $\quad \alpha = 2 \quad c = \frac{2}{3} \quad \phi = w(y)$

$\alpha = 0 \quad c = 0 \quad \phi = w(y)$

This seems to indicate a "C" shaped curve on the α vs. R plot. Howard points out that further analysis is necessary to clarify what is meant when $\alpha \to 0$ and $R \to \infty$ as the combination αR is important in the original equation. The qualitative observation about the neutral stability curve is born out, however by the final theoretical results.

Howard at this point expands an integral equation derived from the Orr-Sommerfeld equation in powers of α and solves numerically on the IBM 704 Computer. Tatsumi and Kakutani expand the Orr-Summerfeld equation in powers of $\frac{1}{\alpha R}$ for $R \gg 1$ and in powers of αR for R small. Curle just neglects the fourth order term, which has very doubtful physical validity, but gives about the same result as the other methods.

The neutral stability curve looks like this:



Howard's final equation is:

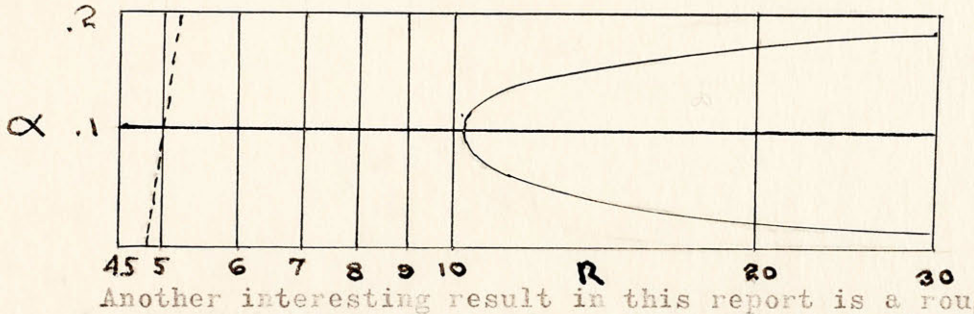
$$\alpha = \frac{.954}{R^2} + \frac{5.4}{R^4} \cdots$$

This establishes the minimun Reynolds number below which no infinitesimal disturbances can grow at $R=4$.

This Reynolds number is based on the mean velocity of the jet, the diameter of the nozzle and the fluid properties of the fluid.

$$R = \frac{\rho v d}{\mu}$$ ρ - density v - mean velocity
μ - viscosity d - nozzle diameter

There is a report by a group of people from Pennsylvania State University that cites a different value for this critical Reynolds number in a 2-dimensional laminar jet. By use of the Galerkin method, making use of only a single term approximation, the curve derived is as follows.



Another interesting result in this report is a rough minimun Reynolds nimber calculation due to Pai. By use of relativity simple algebraic arguments, Pai finds the condition represented by the dotted line in the above graph as the minimun Reynolds number for instability.

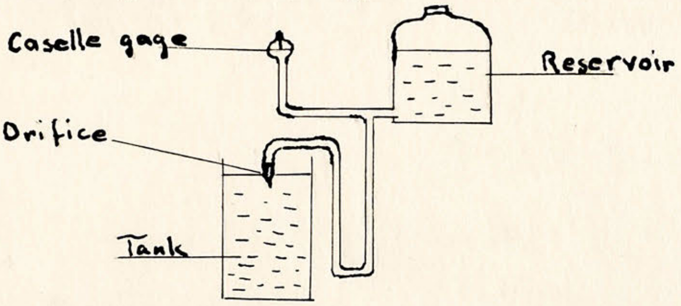
EXPERIMENTAL BACKGROUND

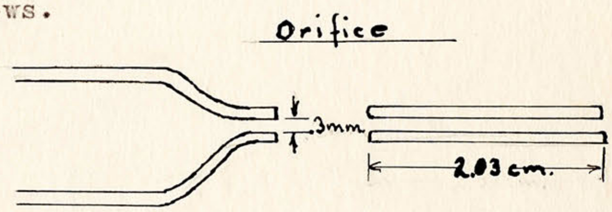
Brown, Savic, and Andrade did some research on jets with free boundaries in England around 1939 and some work has been done in Germany by Wille and his associates around 1951. No other experimental data on full jets with free boundaries was found by the author.

Brown in his experiments made some measurments on the velocity profile of the free jet and described how the disturbance wave number varies as a function of distance from the nozzle. Savic has taken some of Brown's pictures and developed a new way of deducing the frequency data . Wille and his associates have mainly been interested in describing how the vortices produced in the unstable jet decay and what the effect ~~of~~ is of superimposed disturbances. The original work of Wille where he is reported to have taken movies of water jets was unavailable to the author.

Andrade's experiments come closest to the experiments in this thesis. In 1939 Andrade made some observations with a thin long slit. He made extensive measurements of velocity profiles as a function of distance from the orifice and described the decay of disturbances qualitatively. Andrade, however, passes over the problem of minimun critical Reynolds number and apparently used only one slit width in his work.

A diagram of his apparatus is as follows.





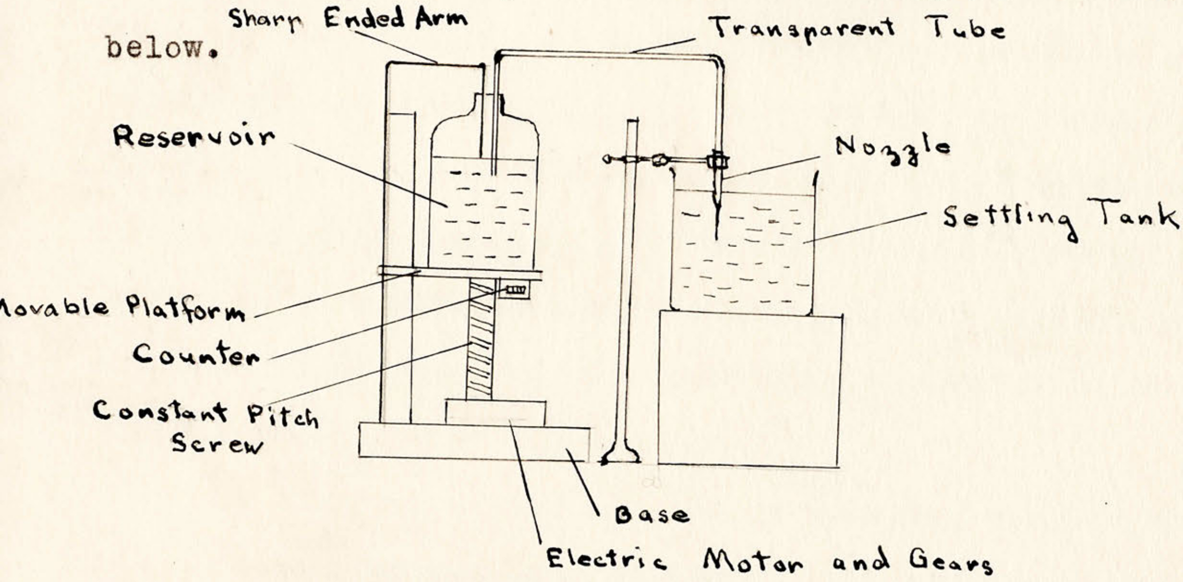
Andrade reports observing disturbances in his jet down to a Reynolds number of 10.

EXPERIMENTAL APPARATUS

There are three things that have to be measured in determining the minimum Reynolds for instability of the water jet These are the volume flow rate, the diameter of the nozzle exit section, and the temperature of the water.

The apparatus has to be designed so as to make visual observation of the water jet possible and to maintain a constant Reynolds number for a sufficiently long time to make the necessary measurements for determining the Reynolds number.

An idealized representation of the apparatus is given below.



The essential part of this apparatus is the movable platform on which the reservoir sits. This platform can be raised and lowered by an electric motor and the motion of ~~this motion of~~ this platform is measured by a counter geared to the shaft on which the platform rides. The shaft is actually a finely machined constant pitch screw which enables the counter to read to thousandths of an inch. To stabalize the platform there is a heavy post that runs from the base of the apparatus and which is connected to the platform by a sliding fitting. This whole piece of apparatus is remarkably sturdy and it is quite true that if the mechanism would have to have been built for this experiment, an easier answer would have been available. For instance a Caselle gauge like the one used by Andrade could have been used.

The flow out of the reservoir is measured by finding the drop in reservoir height over a period of time. This is done by having a fixed sharp-ended matal arm which is attached to the base of the platform and the sharp end of which is made to just touch the surface of the water in the reservoir, each time a flow rate measurement is taken. Time is measured with an electric wall clock. The surface area of the water in the reservoir was determined by weighing the water corresponding to a certain drop in reservoir height and looking up the absolute density of the water at the measured temperature of the water.

The diameter of the nozzles is measured with an optical conparator. The optical comparator that was used was built by Jones and Lansom and magnified the nozzle section by a factor of 62.5. The construction of the comparator is simple and consists of just a set of lenses, a mirror, and a light source. The image of the object is projected on a screen for the necessary measurements. The focus of the comparator is fairly sharp and very little error is involved in the use of this instrument.

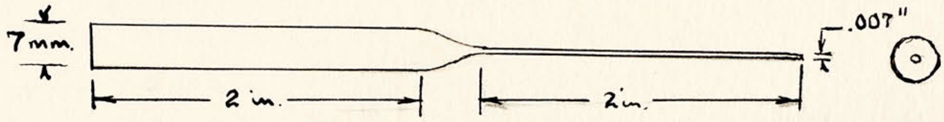
The thermometer used to measure reservoir and settling tank temperatures is calibrated in degrees of centigrade.

The liquid that was observed is water to which a small amount of NaOH and phenolthalin disolved in alcohol is added. The color of this mixture is a deep red. As the settling tank contained just water, the jet of red liquid is clearly visible.

The reservoir is a glass jar with a capacity of about two liters and the receiving tank is a pyrex two liter beaker.

The tubing from the reservoir to the nozzle is made of transparent plastic and has an inside diameter of about 7mm.

The nozzles are drawn from 7mm. glass tubing. The glass tubing was heated in a gas torch and drawn to various inside diameters. Typically the nozzles appear as follows. They have approximately constant diameter section at the fine end which extends for over an inch.



The nozzle tips were ground square by hand before the nozzles were used.

EXPERIMENTAL PROCEDURE

The steps necessary for measuring the Reynolds number that corresponds to a qualitative observation of the jet behavior were as follows. A flow was induced in the nozzle by raising the platform to a height so that the reservoir level is higher than tank level. The reservoir is then pumped up to a pressure sufficient to start a flow through the nozzle. The reservoir is then brought back to atmospheric pressure and the platform moved to a position where one observes the desired type of flow in the jet. The sharp ended arm, which is adjustable between runs, is then bent so that it just touches the water line. A slight movement of the platform was frequently necessary to obtain this correspondence. At the instant when the arm touches the water line the time is recorded. With the range of nozzle sizes used, the water line of the reservoir would drop about .040 inches in an hour for the Reynolds numbers of interest. As the difference between reservoir and tank levels was usually about two inches, the second observation was taken approximately a half hour later and it was assumed that the Reynolds number had not changed in this time. The second observation consists of raising the platform until the reservoir water line is again just in contact with the arm and recording the time when this occurrs. The temperature of the liquid was usually measured after taking each data point.

The above procedure, with the exception of initiating the flow, has to be repeated for each observation of the jet behavior where the Reynolds' number is desired. For the same nozzle, it was found desirable to measure a point where the jet was laminar throughout all its range where it was turbulent without a doubt, where one could just see turbulence, and where induced oscillations would not die out very quickly.

After sufficient information is thus collected to bracket the Reynolds number of neutral stability, the end of the nozzle is broken off and put into the optical comparator. The nozzle is looked at on end and the exit plane put into focus. This enables the nozzle cross-section geometry to be determined and at the same time measurments to be made of the nozzle diameter.

DISCUSSION OF RESULTS

Before a discussion of the minimun Reynolds number for instability is undertaken, it is necessary that the qualitative observations of the jet on which the decision was made, as to whether the jet is or is not stable, be understood.

If the jet be first observed at a fairly high Reynolds number, of about fourty, and the Reynolds number decreased to where it was around five, the following changes would be observed to occur in the jet. At the beginning the jet would be regular for the first portion, but as it would increase in diameter and slow down it would break into a ripple which could be described as a series of ring vortices. As the Reynolds number was decreased by decreasing the head of water between the reservoir and the tank, one would observe the distance between the nozzle exit plane and where the flow breaks into the ripple, to decrease. Finally, the jet would be smooth for its whole length except for an intermittent little ripple at the edge of the jet, very close to the nozzle which would grow and then disappear again. The jet would be described here as very slightly turbulent. As the Reynolds number is decreased even further no self excited disturbances could be observed. Oscillations were superimposed on the jet at this step by slightly jarring the apparatus. If the oscillations were not observed to damp out rapidly, it was judged that the jet was almost not laminar, when this Reynolds number was decreased even more and when induced oscillations were damped out almost immediately the jet was said to be definately laminar.

The measurments for these qualitative observations were made and it was found that for a range of nozzle diameters between 5.2 to 18 thousanths of an inch and liquid temperatures from 13 C to 30 C transition between slightly turbulent and almost not laminar occurred at a Reynolds number between 11 and 10. This is contrasted with theoretical predictions for this transission for a Reynolds number of 4.

There are three possibilities that could contribute to this discrepancy that appear immediately. First, the flow does not remain parallel upon leaving the nozzle as assumed in the theory. Second, there is a change from a Poiseuille velocity distribution to the $\mathrm{sech}^2 y$ law assumed in the theory which may pose problems close to the nozzle. Experimental data taken at higher Reynolds number by Andrade and Brown does not however suggest this. Third, there was no way of acquiring an understanding of what the growth rate and wave number of the oscillation predicted by the theory at Reynolds number of about 10 meant in physical terms. For instance, the growth rate of a disturbance could be so slow that nothing observable would happen before the Reynolds number in the flow would be down to four due to the spreading out of the flow.

The real reason is probably a combination of there effects. What must be stressed is, however, that the answer given by theory would not be predicted in the first place. Tatsumi in his paper for instance calculated that the component of velocity perpendicular to the stream is half stream valvue at a Reynolds number of four. This of course invalidates any parallel flow assumptions. Finally, the inflection point in the velocity profile of a cylindrical jet on which instability is really dependent is not a true inflection point.

In view of these difficulties it is hard to place any significance to the good agreement between the results obtained in the experiments and the curve derived in the Pennsylvania State University report mentioned in the discussion on theory. A real comparison of experiment with theory would require a simultaneous measurment of the wave number of the disturbance and the Reynolds number of the jet when the jet is very slightly turbulent. An attempt to do just this was made but was unsuccessful. One method that was tried was to sincronize the disturbance frequency with a strobe light frequency. This failed because the disturbance was intermittent and very hard to see. Another method that was tried was to take pictures of the jet. A polaroid camera with portrait lense was available but had insufficient resolution to separate the disturbance from the main jet.

The situation is, however, not hopeless. The disturbances are visible with the naked eye and rough estimates can be made of wave length. An α of .5 was estimated at one point by taking the disturbance propagation speed as the mean speed of the flow and making an estimate of the wave length of the disturbance from visual observation of the jet. To be sure this could be off by more than a fractor of two, and such observations are far from useful in trying to differentiate between an α of .1 corresponding to the minimun Reynolds number in the Pennsylvania State University report and the corresponding α of about .2 derived by Howard, Curle, and Tatsumi.

A suggested method for measuring the disturbance wave number is to focus two precision cameras on the jet and trip them with a pre-determined time delay. If some reference length is included in the pictures, this would be all that is necessary to measure α .

While an α vs. R minimun for instability, plot, determined experimentally, would be the best comparison with theoretical results. It is significant in itself that the minimun Reynolds number does not vary with either the diameter of the nozzle or the viscosity of the fluid. This bears out the assumption that only the Reynolds number is the significant quantity in this stability problem.

Before a final conclusion about the experimental results can be made, a careful analysis of possible errors has to be undertaken. The biggest possible source of error in the results is the uncertainty involved in the flow rate measurment. A consistent method of raising the platform until the sharp ended arm touched the reservoir surface was very difficult. As one would expect, the fluid would jump the gap between the arm and the reservoir surface. This is not serious in itself as no error is introduced if the reservoir surface is always calm and the water jumps the gap from the same distance. Disturbances in the laboratory, due to people walking would, however, cause ripples on the water which would change the gap over which the water would jump. The error introduced in this way was as great as two thousanths of an inch. The percent error in the Reynolds number of course depends on how many thousanths of an inch the reservoir level had changed.

The time measurment between two data points would never be in error by more than a minute. This would not affect the Reynolds number by more than 3%. The only significant error in measuring the nozzle exit diameter occurred in cases where the nozzle was not perfectly circular. An equivalent circular nozzle section was determined in such cases by measuring the major and minor axis of the elliptic shape and interpolating. As the major axis and minor axis never differed by more than 10% of the major axis the error thus incurred affected the Reynolds number by less than 2%. The temperature measurments caused less than 1% error in the results as far as the mechanics of measuring with a thermometer is concerned. The real problem was that the reservoir and tank would be at different temperatures in certain days. This temperature difference was sometimes as much as 1.5 C. and amounts to a 3% change in the viscosity of water. Whenever such a discrepancy occurred, the reservoir temperature was used.

A definately second order effect was the change in Rynolds number caused by the decrease in the head of water between the reservoir and tank, due to the flow through the nozzle. Only in tubes with large diameters of about 17/1000 of an inch and at low Reynolds number would this be noticeable. In such cases the change was observed to be from a Reynolds number of 11 to one of 10, in an hour. As the tubes got smaller the error goes down as the square of the diameter.

Adding all the possible errors it can be seen that the minimun Reynolds number could be off by about 10%. This is certainly not true if all the data points are concidered. The most probable minimun Reynolds number for instability can be said to be within 5% of a Reynolds number of 10.5.

CONCLUSIONS AND RESULTS

The experiments performed in connection with this thésis showed that there is a Reynolds number above which a jet of incompressible viscous fluid is always turbulent and a Reynolds number below which no self-excited disturbances in the jet can be seen. The transition was found to occur at a Reynolds's number between 10 and 11 within an uncertainty of 5%.

The transition was not affected by large changes in nozzle diameter or small changes in the geometry of the nozzle exit section. The transition also was not affected by a range of temperatures from 13°C to 30°C.

The jet was observed to diverge upon leaving the nozzle. The divergence appeared greater at smaller Reynolds' numbers and reached a slope of about 30 at around a Reynolds' number of 6.

The turbulence at Reynolds' numbers of about 30 would be observed as a set of ring vortices suddenly forming from a smooth set at about a half inch from the nozzle exit. As the Reynolds' number would be lowered the half inch distance would be reduced until just a small ripple could be observed at the very edge of the jet near the nozzle, at about a Reynolds' number of 11.5.

While the experimentally determined minimum Reynolds' number for instability does not agree with the theoretical value, this discrepancy is not serious. The fact that the theory includes very slowly growing disturbances and that the theoretical calculations are based on a parallel flow assumption, would tend to predict a lower value than one would observe. The experiments can thus be said to bear out the results of Howard, Tatsumi, and Curle rather than the curve derived by Lew and Fanucci in the Pennsylvania State University report.

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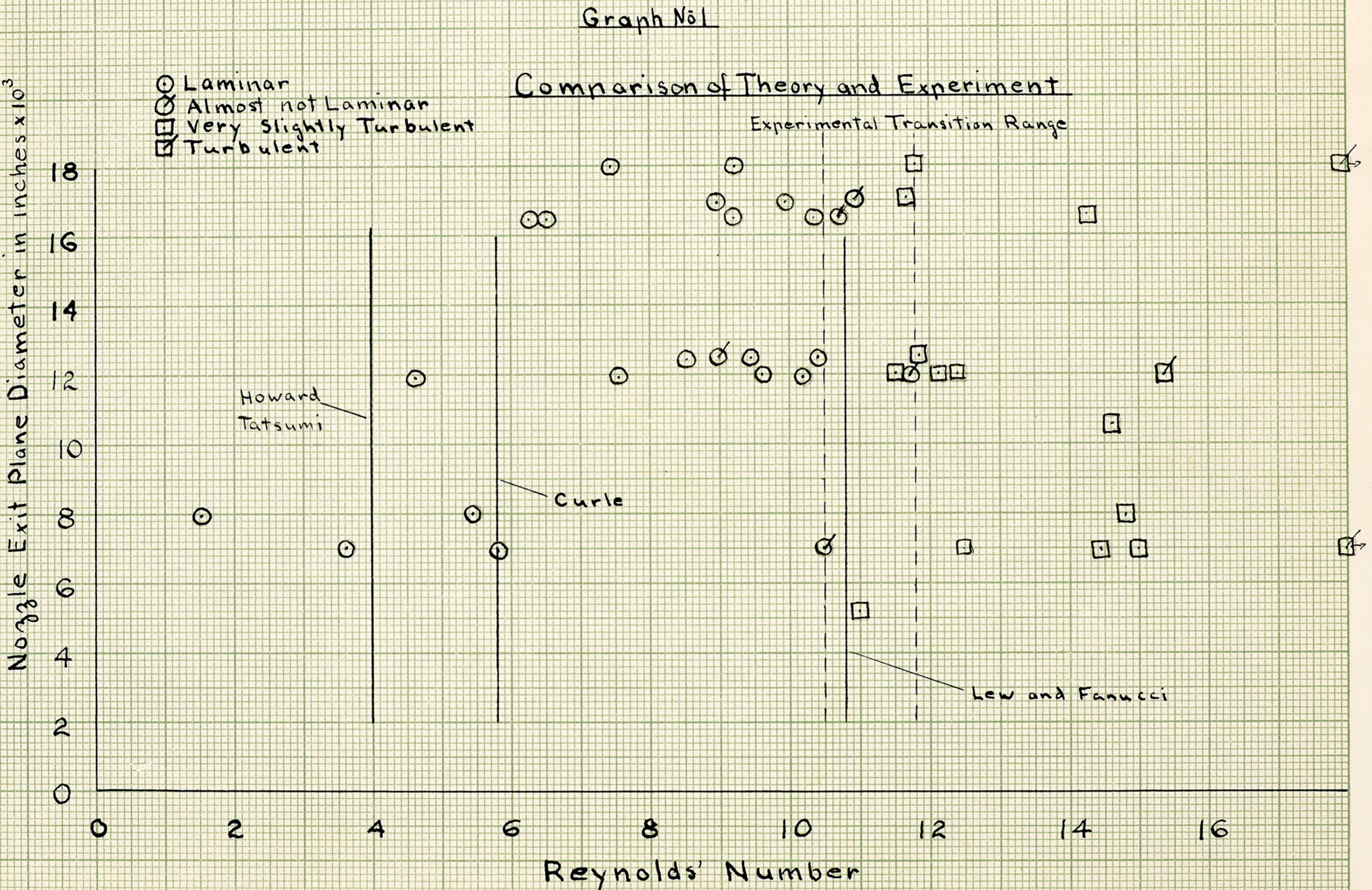
Appendix



Graph No 1

Comparison of Theory and Experiment

Reynolds' Number Calculation

$$R = \frac{\rho v d}{\mu} \qquad v = \frac{Q}{t \times 60 \times \pi r^2} \qquad Q = \Delta h \times A$$

$$R = \frac{\Delta h}{t \times d} \times \frac{2 \times 2 \times A}{\pi \times 60} \frac{\rho}{\mu} \times 10^3$$

v = mean velocity

R = Reynolds' Number

ρ = fluid density

μ = fluid viscosity

d = nozzle diameter in thousanths of an inch

r = nozzle radius

Q = volume of fluid that leaver reservoir

t = time in minutes between two data points

Δh = drop in reservoir level

A = area of reservoir surface

Determination of A

At a temperature of 28°

103.458 grams of water corresponded to a Δh of .401 in.

$$A \times 2.54 \times .401 = \frac{103.458 \text{ g}}{.99823 \text{ g/cc}}$$

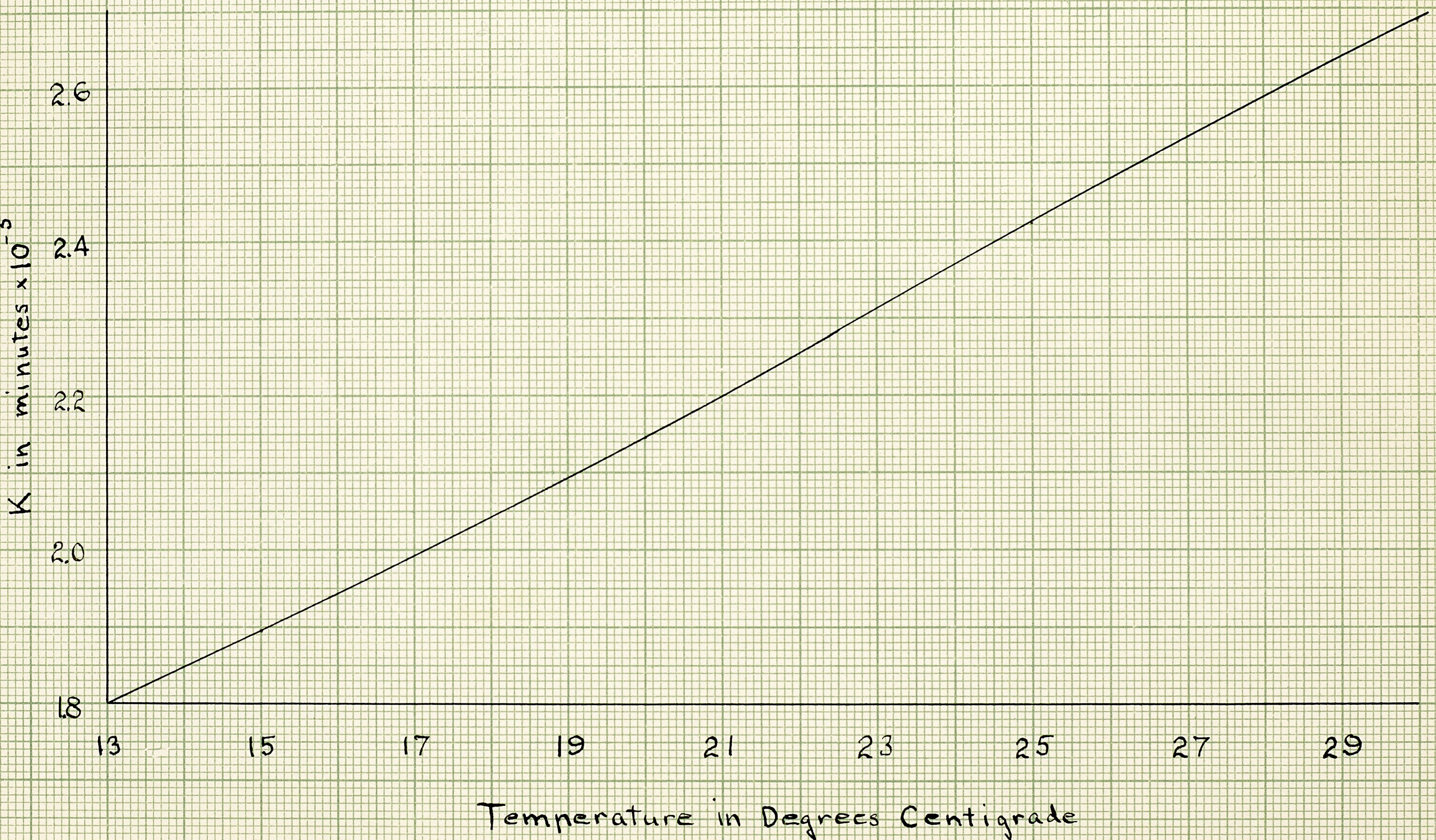
$$A = 101.783 \text{ cm}^2$$

$$R = K \frac{\Delta h}{t \times d}$$

K is just a function of temperature

K is plotted in Graph No 2

Graph No 2


K in minutes × 10^{-5}
2.6
2.4
2.2
2.0
1.8
13
15
17
19
21
23
25
27
29
Temperature in Degrees Centigrade

Expeimental Data

Nozzle A.

Counter Reading in Inches	Reynolds' Number	Time in Minutes	Observations
.306	6.29	2:01	laminar
.317	6.5	2:26	— " —
.337		3:10	— " —

The counter has an adjustable zero which was often changed between runs.

Counter Reading in Inches	Reynolds' Number	Time in Minutes	Observations
.127	14.3	1:44	little turbulent temperature – 24.2°C
.151	10.35	2:08	less turbulent
.172	10.7	2:37	laminar – close reservoir head – $\frac{5}{8}$"
.190	9.25	3:01	— " —
.223		3:52	— " —

temperature 24.2°C

nozzle end section – a perfect circle – $\frac{16.5}{1000}$ inch in diameter.

Nozzle B

Counter Reading in Inches	Reynolds' Number	Time in Minutes	Observations
.257	8.98	3:06	Almost not laminar
.294		4:00	Temperature 13°C

nozzle section – $\frac{13"}{1000}$ by $\frac{12"}{1000}$ ellipse

Nozzle C

Counter Reading in Inches	Reynolds' Number	Time in Minutes	Observations
.024	11.88	12:59	very slightly turbulent – 26°C
.076		2:06	
.026	9.45	2:10	laminar – 26°C
.038	10.45	2:26	"
.059	8.55	3:04	"
.078		3:46	"

Nozzle D

Counter Reading in Inches	Reynolds' Number	Time in Minutes	Observations
1.447	1.55	2:56	laminar
1.451		3:15	— " —
1.565	5.44	3:18	less laminar
1.571		3:54	— " —
1.709	14.8	3:59	slightly turb – 26°C
1.727		4:36	— "

nozzle section – perfect circle $\frac{8"}{1000}$ in diam.

Data (con't.)

Nozzle No1

Counter	Reynolds' Number	Time	Observations
		9:54	slightly turbulent
.754	12.4	11:05	— " — Temp 28°C
.794			
.669 (?)		11:08	Almost not laminar
.698	11.7	12:01	laminar, - level $\frac{5}{8}$"
.727	10.2	1:02	— " —

exit section - perfect circle $\frac{12}{1000}$" diam.

Nozzle No2

		1:42	very slightly Turb.
2.409	11.0		
2.420	on average	2:29	— " —
			temp 28°C
2.428		2:59	slightly turb.
2.445		3:47	— " —
			head of water $2\frac{1}{4}$"

exit section - perfect circle - $\frac{5.2}{1000}$" diam.

Nozzle No3

		1:05	little turbulent
.401	13.16	1:58	— " —
.439	14.7	2:38	still slightly turb
.471	12.87	3:08	— " —
.492	11.55	3:43	almost laminar
.514			Temp 28°C

exit section - circle $\frac{14}{1000}$" diam.

Nozzle No4

.515	11.7	11:08	slightly turb
.553	10.98	11:59	almost not laminar
.598	9.95	1:01	laminar
.625		1:42	— " —
.653	8.99	2:29	— " —

exit section $\frac{17}{1000}$" diam

reservoir temp 30°C

tank temp 28°C

Data (con't)

Nozzle No 5

Counter	Reynolds' Number	Time	Observations
		2:53	very turbulent
1.999	21.10	3:26	— " —
2.018			
1.260	10.5	3:34	almost not laminar
1.268	15.	4:02	— " —
1.274		4:16	slightly turb.
.8785		11:42	laminar
	5.8		
.887		12:36	— " —
	3.6		
.890		1:12	— " —
1.652	12.5	2:25	turbulent slightly
1.666	14.45	3:06	— " —
1.692		4:12	— " —

exit section - circle $\frac{7''}{1000}$ in diam.

reservoir 30°C

tank 28.5°C

Nozzle No 7

		1:37	very turbulent
.573	19.2	1:53	— " —
.594			temp 18.2 °C
.404		1:56	slightly turb
.482	11.85 on average	3:32	— " —
		4:01	temp 18.2°C
.510			— " —
.511		3:09	laminar
	9.21		temp 27.2°C in reservoir 25.5° in tank
.525		3:30	
.547	7.42	4:11	laminar

exit section a $\frac{20''}{1000}$ by $\frac{16''}{1000}$ ellipse

Data (con't.)

Nozzle No 8

Counter	Reynolds' Number	Time	Observations
.246	12.2	11.42	very slightly turbulent
.294		1:01	— " —
.297	7.54	1:03	laminar
.327		2:14	— " —
.358	9.65	2:19	laminar
.392		3:19	— " —

end section – $\frac{11}{1000}$" by $\frac{13}{1000}$" ellipse

tank 25°   reservoir 23.5°

Nozzle No 9

1.132	11.6	11:37	slightly turb
1.151		12:06	— " —
			temp 27° C
1.325		12:12	turb.
	18.75		
1.372		1:09	turb.
	15.4	1:50	laminar
1.402			
	4.6	3:08	— " —
1.419			

Reservoir water buoyant – uncertain results

nozzle end section – diam. $\frac{12}{1000}$" – circle

Nozzle No 10

1.413	14.6	2.19	slightly turb.
1.438		3.00	— " —

Temp. 27°C

$\frac{10.5}{1000}$" diam end section – not a perfect circle