Effect of Surface Roughness on the Delayed Transition on 9:1 Heated Ellipsoid

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To quantify the effects of distributed surface roughness on the delayed laminar-turbulent transition of a thermally stabilized boundary layer in water, measurements were made on a 50 mm diameter 9:1 fineness ratio ellipsoid for various surface roughness, heating and flow conditions. Boundary-layer transition locations were determined for length Reynolds numbers ranging from 3.0 to 7.0×10^6. The ellipsoid was tested at three different surface heating levels. For each surface roughness condition (4, 1.9 and 0.15 μm finish) transition measurements were made for the ellipsoid with no heating; $\Delta T = 10$ and 15°C, where ΔT is the difference between inlet interior water temperature and freestream water temperature. The results can be summarized as follows; for each reduction in surface roughness, the performance of the model, as judged by length of laminar flow, improved for all three heating conditions. Increases in the amount of surface heat addition corresponded to increases in sensitivity of transition location to roughness. For the smoothest body with the largest amount of surface heating an increase of 81% in laminar flow length over the no heating case was achieved at a length Reynolds number of 5.25×10^6.

Nomenclature

B	= small burst rejection ratio
k_{rms}	= root mean square surface finish, m
k_s	= height of roughness element, m
L	= reference length of model, m
N_h	$= \sigma t_h$
N_t	= total number of samples exceeding V_t of the last N_h
Re_L	= Reynolds number based on $L = 450$ mm, $U_\infty L/\nu$
T_e	= model exit water temperature, °C
t_h	= hold time, s
T_i	= model inlet water temperature, °C
T_∞	= freestream water temperature, °C
U_∞	= freestream velocity, m/s
u'	= fluctuating velocity component in x direction, m/s
V_t	= threshold level, V
X_t	= transition location axial distance from the nose, m
ΔT	$= T_i - T_\infty$, °C
σ	= sampling frequency, samples/s
θ_l	= laminar boundary-layer momentum thickness, m
ν	= kinematic viscosity of water, m²/s

Introduction

THE laminar to turbulent transition of a boundary layer can be affected by many variables: pressure gradients, mechanical vibrations, freestream flow disturbances, etc. In this study the interaction of two of these variables, surface roughness and surface heating, as it relates to boundary-layer transition, was investigated.

The delay of laminar-turbulent transition by surface heating in water has been experimentally verified, and a transition Reynolds number of 47×10^6 has been achieved in a near zero pressure gradient flow tube by Barker and Gile.[1] The calculations of Wazzan, et al.[2,3] have predicted transition Reynolds numbers as high as 200×10^6 for a heated, zero pressure gradient flat plate. Clearly, surface heating in water can be an extremely effective method of drag reduction for small, high-speed underwater vehicles. If a laminar boundary layer can be maintained over a major portion of the vehicle's surface, drag reduction of about 4 or 5 times can be achieved, resulting in the associated reduction in propulsive power required.

In an analytical study by Kosecoff et al.[4] the qualitative effects of distributed surface roughness on the stability of a heated boundary layer were predicted. Kosecoff et al. combined linear stability theory with the assumption that the distributed surface roughness modifies the mean flow profile. The conclusion reached was that the stability of the boundary layer is affected, such that in the presence of surface heating there exists a roughness level "threshold" below which the boundary layer behaves as if it were adjacent to a smooth wall. Kosecoff et al. go on to predict that as the roughness threshold is exceeded the stabilizing effect of surface heating is diminished until at some point surface heating no longer stabilizes the boundary layer but is in fact a destabilizing influence.

In an effort to quantify the effects of some real world surface roughness on a thermally stabilized boundary layer in water, an experimental study has been carried out. The goal of the study was to acquire experimental data on the effect of three different levels of distributed roughness on the delayed transition of a heated ellipsoidal model in a controlled test environment.

Flow Facility, Model, and Instrumentation

The experiments were conducted in a high-speed water tunnel. The water-tunnel has a 0.305-m-diam horizontal open jet test section which can accommodate models up to 0.75 m in length. Flow velocities up to 14 m/s can be achieved with a turbulence level of about 0.16% (u'/U_∞) throughout the speed range. Optical access to the test section is obtained through eight 0.25×0.75 m, 0.025-m-thick acrylic windows. Axial velocity measurements in the boundary layer were obtained with a laser Doppler velocimeter (LDV), mounted on a three-dimensional traversing system. This velocity signal was then processed to obtain a value for the transition location as will be described in the next section. The LDV optical system consisted of a 15 mW He-Ne laser, collimator, mirror system, beam splitter, 3.75× beam expander, and a 152 mm diam × 762 mm focal length lens, arranged in a conventional dual beam forward-scatter configuration. Receiving optics were located on the opposite side of the test section. Measurement volume dimensions were 0.12 mm

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diameter and 2.0 mm length. With the forward-scatter arrangement, velocity measurements could only be made directly above or below the model. Tunnel water was seeded with 1.5 μm silicon carbide particles to increase the data rate of the counter type LDV signal processor to about 8000 samples/s for most flow conditions.

Figure 1 shows the sting mounted 9:1 fineness ratio ellipsoid of revolution used for this test. The body maximum diameter was 50 mm, which maintained a true elliptical outline until an axial distance of 395 mm, where the radius assumed a constant slope to intercept the sting diameter of 25.4 mm. The reference length L used in the presentation of results was 450 mm, the untruncated ellipsoid length. The hollow body shell was machined from type 304 stainless steel, with a nominal thickness of 3.5 mm. Heating of the body was achieved by pumping externally heated water through the interior of the shell in a parallel flow configuration. Maximum interior water temperature was about 15°C above ambient, which at maximum internal flow rate produced an average surface heat flux, over the forward 395 mm of model length, of 11.4 kW/m^2 for fully laminar external flow to 17.0 kW/m^2 for mostly turbulent external flow. Maximum internal flow rate was 6.35 liter/min. The only instrumentation internal to the model was a thermistor to measure water inlet temperature T_i, and two thermistors to measure water exit temperature T_e, from which heat input could be calculated. Other parameters measured were tunnel pump speed (rpm) and ambient water temperature T_∞, from which freestream velocity and flow Reynolds number were deduced. Surface roughness distributions were measured with a profilometer over the length of the model.

Surface Roughness

During the original manufacture of the ellipsoid shell, machining marks were left on the external surface. Consequently, the type of distributed roughness present on the model was a series of grooves around the circumference of the shell, in the crossflow direction, with an rms height of 4.0 μm. This was the initial surface finish tested. The spacing between grooves was approximately 0.35 mm. The roughness of the first 25 mm of the nose was about 2.0 μm rms. Two smoother finishes were produced by further machining of the shell; the intermediate roughness tested was 1.9 μm rms and the final test was with a 0.15 μm rms surface finish.

Determination of Transition Location

For this study boundary-layer transition was defined to be the location where the boundary layer was alternately laminar and turbulent for an equal amount of time (i.e., 50% intermittency). An intermittency of 0% corresponds to a fully laminar boundary layer and 100% intermittency is completely turbulent flow. Intermittency was measured by locating the center of the LDV measuring volume, at a distance of $5.85\theta_l$ away from the model wall, where θ_l is the momentum thickness of a laminar boundary layer for the given flow conditions. The momentum thickness was determined by an integral method boundary-layer calculation[5] using an experimentally determined pressure distribution. The value of $5.85\theta_l$ was chosen to place the LDV measuring volume outside the region of sharp velocity gradient, in order to avoid the effects of the finite measuring volume diameter (0.12 mm) and the sporadic characteristic of LDV signals, which would produce a fluctuating velocity output signal indistinguishable from turbulence, even in fully laminar flow.

The LDV photodetector signal was processed in the usual way with a counter type signal processor giving an analog output proportional to velocity. The analog velocity signal was bandpass filtered (50-2000 Hz) and amplified before real time signal processing by a Cromemco Z-2D digital computer [Z-80A central processing unit (CPU)]. Amplitude of the filtered velocity signal was adjusted for each run such that the maximum velocity excursion of the turbulent portion of the signal never exceeded ±10 V, the input range of the analog/digital (A/D) converter.

The main data reduction program was written in FORTRAN. Due to execution speed limitations, the real time signal processing subroutine (INTER2) was written in Z-80 assembly language. The CPU instruction execution time limited A/D sampling speed to 3333 samples/s (300 μs per sample). Although this was not fast enough to reliably reconstruct the original signal, no problems were observed in the algorithm used to determine intermittency. Figure 2 shows a typical signal (after filtering) and the corresponding indicator function produced by the computer. A value of zero for the indicator function indicated laminar flow and ten (volts) turbulent flow.

The subroutine INTER2 which determines intermittency uses three variables—the threshold value V_t, the hold time t_h, and the small burst rejection ratio B—as criteria for the determination of intermittency. The threshold value V_t is the value which a velocity signal must exceed in order to be considered turbulent. The hold time t_h is the duration of the time interval, which begins when the velocity signal exceeds V_t. The hold time basically represents the time interval over which the threshold value is applied and is used to prevent the intermittency indicator from changing state for small time scale events of duration less than t_h. The small burst rejection ratio variable B is the criterion used for determining if the initial time interval contains a noise spike or is a legitimate turbulent burst. Values for the variables V_t, t_h, and B were determined by observation of a large number of turbulent bursts and the resulting indicator function as outputted by INTER2 (Fig. 3) on a storage oscilliscope. Using this calibration technique $V_t = 1.0$ V (10% of maximum turbulent fluctuation), $t_h = 6$ ms (a very short time compared to the

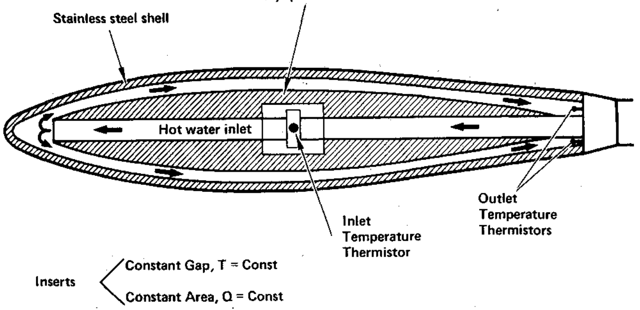

Fig. 1 Cross section of heated ellipsoid model (not to scale).

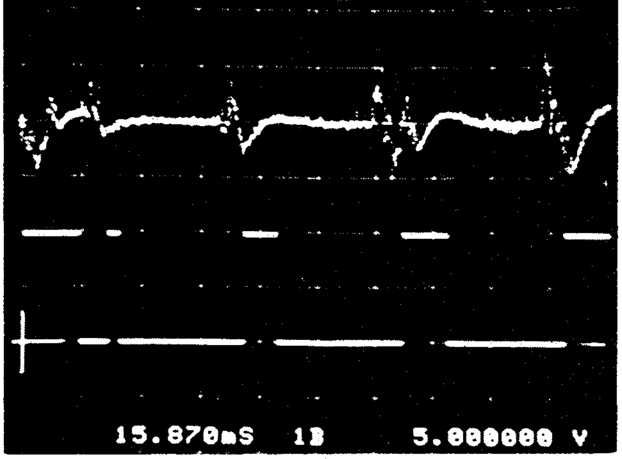

Fig. 2 Filtered velocity signal (upper trace) and indicator function (lower trace). Note 6.0 ms delay (1 holdtime) between turbulent burst and indicator.

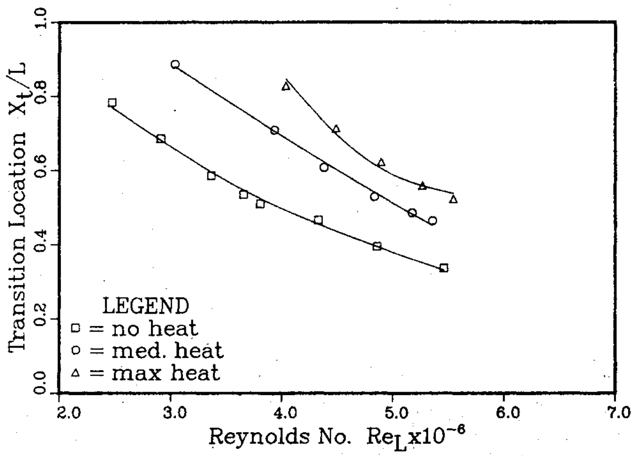

Fig. 3 Transition location of ellipsoid model with 4.0 μm rms finish.

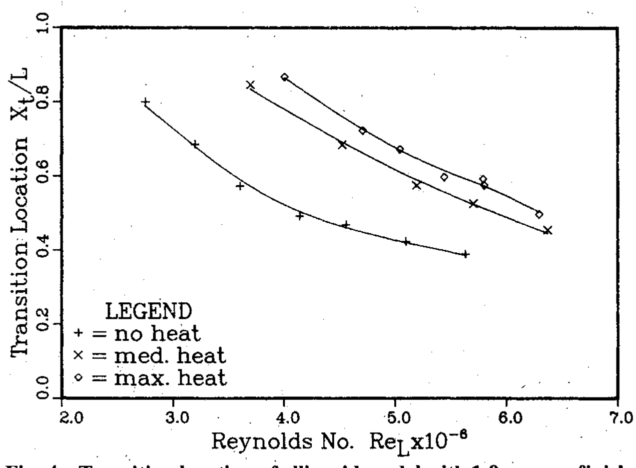

Fig. 4 Transition location of ellipsoid model with 1.9 μm rms finish.

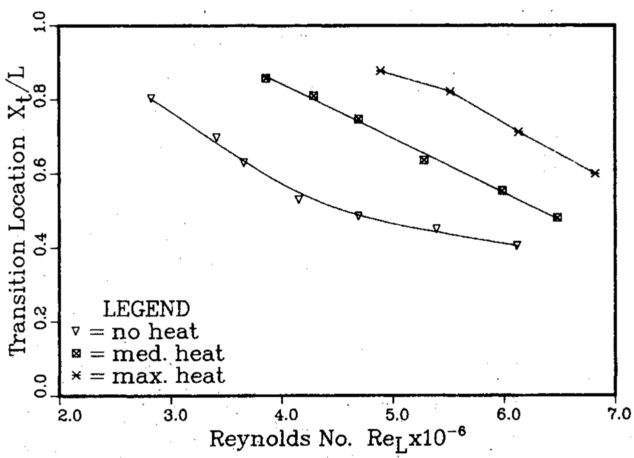

Fig. 5 Transition location of ellipsoid model with 0.15 μm rms finish.

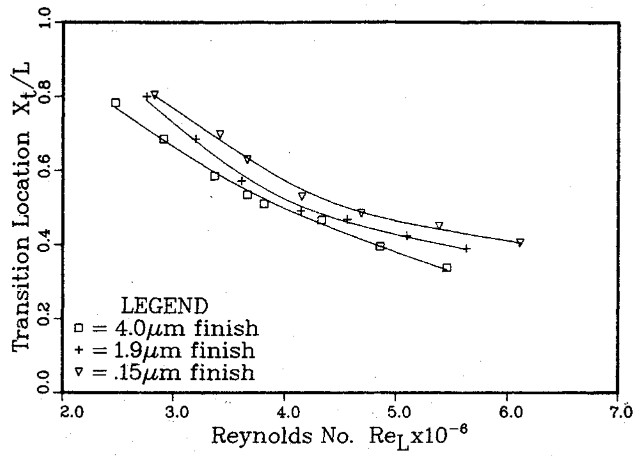

Fig. 6 Transition location of ellipsoid model with no heating, 3 finishes.

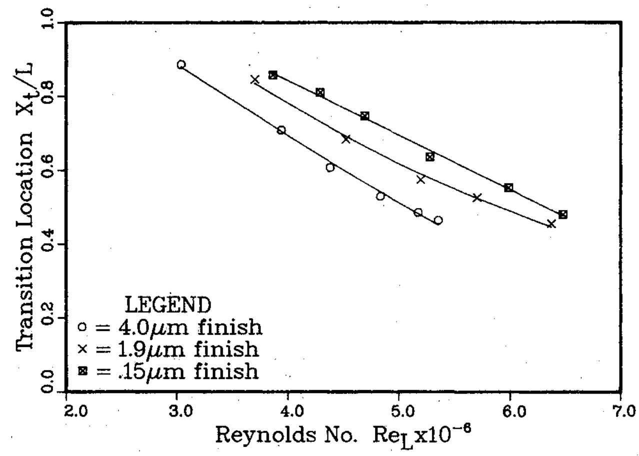

Fig. 7 Transition location of ellipsoid model with medium heating ($\Delta T = 10°C$), 3 finishes.

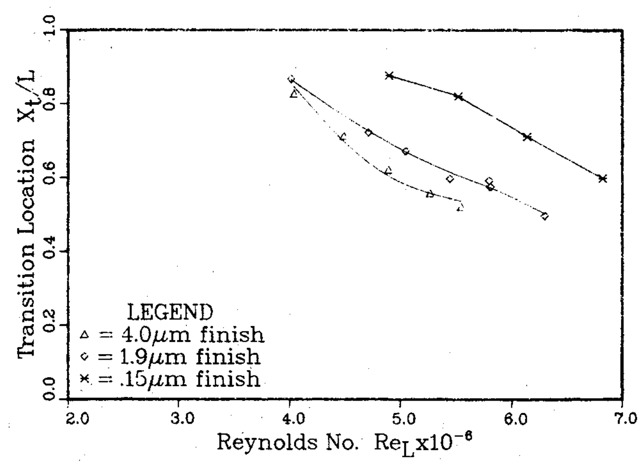

Fig. 8 Transition location of ellipsoid model with maximum heating ($\Delta T = 15°C$), 3 finishes.

length of a turbulent burst), and $B = 0.3$ were judged to be appropriate values for the variables.

The total number of samples taken during a holdtime is N_h ($= \sigma t_h$) and the number of those samples above V_t is N_t. INTER2 makes an intermittency determination based on the following algorithm. For an initially laminar velocity signal, if $N_t = 0$ or $N_t/N_h \leq B$, the flow is assumed to continue laminar (the second condition eliminates short duration noise pulses above V_t). For a change in the state of the indicator function from laminar to turbulent, $N_t/N_h > B$. For a continuing turbulent indicator function, $N_t > 0$. To re-establish a laminar value for the indicator function, $N_t = 0$.

The algorithm is evaluated once each sample period. The values returned by INTER2 are the total number of samples taken, the number of samples considered to be part of a turbulent burst, and the total number of bursts, from which intermittency and burst rate can be determined.

For each intermittency value a minimum of about 30 s and a maximum of 120 s of data were taken, the actual time depending on the value of the standard deviation of the running average intermittency (computed every 10 s). A faired curve through a minimum of three intermittency values (vs axial location) were used to determine the location of 50% intermittency of both the top and bottom of the model for a given flow condition.

Results

The location of 50% intermittency for three heating conditions and three surface finishes (4, 1.9, and 0.15 μm) was determined for length Reynolds numbers ranging from 3.0 to 7.0×10^6. The three heating conditions tested as denoted in Figs. 3-8, no heating, medium heating, and maximum heating, corresponded to a constant temperature differential between the incoming model heating water T_i, and the freestream water temperature T_∞, of 0, 10, and 15°C, respectively. The transition locations in Figs. 3-8 are an average of measurements made on the top and bottom of the model.

Figures 3-5 show the improvement of the performance of the model, as judged by length of laminar flow, at each surface finish with increasing surface heating. For the 4.0 μm surface finish model (Fig. 3), at a length Reynolds number of 5.25×10^6, there was a 60% increase in laminar flow length from the no heating to the maximum heating case. The 1.9 μm finish body (Fig. 4) achieved an increase of 64% in laminar flow length at $Re_L = 5.25 \times 10^6$, while the smoothest body, the 0.15 μm roughness model (Fig. 5), improved its laminar flow length 81% for the same Reynolds number.

The trend of increased sensitivity to surface roughness for each increase in surface heating is presented in Figs. 6-8. In the no heating case (Fig. 6), as the body was smoothed from a 4- to a 0.15-μm finish the laminar flow length, at $Re_L = 5.25 \times 10^6$, improved by 22%. For the medium heating (Fig. 7) and maximum heating (Fig. 8) cases ($Re_L = 5.25 \times 10^6$) the laminar flow length improved 35.4% and 46.5%, respectively.

Conclusions

A traditional criterion for the maximum size of distributed roughness (sand grain) that will effect laminar-to-turbulent transition in an adiabatic boundary layer[6] is that $U_\infty k_s / \nu = 120$, where k_s is the average size of the roughness elements. This value is weakly dependent on pressure gradient and turbulence level.[7] For this experiment, assuming a near sinusoidal profile of the roughness grooves, $k_s \simeq 2\sqrt{2} k_{\text{rms}}$, where k_{rms} is the measured surface finish (the definition of k_s implies that the peak to valley height is the important dimension). At a Reynolds number of 5.25×10^6 and $k_{\text{rms}} = 4.0$ μm, the value of $U_\infty k_s / \nu$ is 132, only nominally higher than the traditional value of 120. Likewise, for surface finishes of 1.9 and 0.15 μm the value of $U_\infty k_s / \nu$ is 63 and 5, respectively. Figure 6 shows that under no heating condition, improvement of surface finish from $U_\infty k_s / \nu = 132$ to 5 had only a modest effect on length of laminar flow. However, the substantial performance improvement in the high heating case (Fig. 8) shows that the criterion $U_\infty k_s / \nu = 120$ is not appropriate for heat stabilized laminar flow, with the grooved type of surface roughness tested. For this case the large performance improvement from 1.9 to 0.15 μm rms finish implies that $U_\infty k_s / \nu$ should at least be less than 50 and quite probably a value of 10 or less is realistic. In addition there was no evidence that there was any destabilizing effect of heating over the range of surface finishes and Reynolds numbers tested.

Acknowledgments

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