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Convective Heat Transfer From Castings of Ice Roughened Surfaces in Horizontal Flight

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CONVECTIVE HEAT TRANSFER FROM CASTINGS OF ICE ROUGHENED SURFACES IN HORIZONTAL FLIGHT

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Abstract

A technique was developed to cast frozen ice shapes that had been grown on a metal surface. This technique was applied to a series of ice shapes that were grown in the NASA Lewis Icing Research Tunnel on flat plates. Eight different types of ice growths, characterizing different types of roughness, were obtained from these plates, from which aluminum castings were made. Test strips taken from these castings were outfitted with heat flux gages, such that when placed in a dry wind tunnel, they could be used to experimentally map out the convective heat transfer coefficient in the direction of flow from the roughened surfaces. The effects on the heat transfer coefficient for parallel flow, which simulates horizontal flight, were studied. The results of this investigation can be used to help size heaters for wings, helicopter rotor blades, jet engine intakes, etc., for de-icing or anti-icing applications where the flow is parallel to the iced surface.

Introduction

The primary objective of this experimental work is to have an accurate determination of the values of the convective heat transfer coefficient ,"h", at the surface of an accreted ice shape. These values are useful in helping to size thermally-based de-icing and anti-icing systems, such as electrothermal deicers. They can also be used to help improve ice shape predictions as well as electrothermal deicer performance using computer simulation codes.

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One of the codes that simulates ice accretion along with electrothermal deicer performance is LEWICE, which was developed by the Icing and Cryogenics Technology Branch at NASA-LeRC. The LEWICE code currently uses heat transfer coefficients obtained from an integral boundary layer technique, which are subsequently corrected or adjusted for a non-smooth surface using an equivalent sand-grain roughness approach. The integral boundary layer method being used, as well as the equivalent sand-grain roughness adjustment, are based primarily on empirical relationships which are driven by the computed velocities (from an Euler code) at the top of the momentum boundary layer. It has become apparent in using LEWICE to simulate certain types of ice accretions that the current empirical relationships need to be refined or replaced with relationships that give more representative or physically correct values of "h". To achieve this, a more fundamental understanding is needed of the effect of the special types of surface roughness observed on accreting ice shapes.

The Roughness Problem

For any flow field, both the fluid dynamics and the thermal characteristics are strongly affected by the surface condition of a solid wall. This phenomenon becomes particularly important in applications where roughness is an inherent feature. Because of their frequent occurrence in practice, roughened surfaces have gained a lot of engineering interest and have received prolonged serious study. Examples include missiles, heat exchangers, pipes, turbine blades, naval architecture, aeronautics, nuclear reactor applications, and, recently, aircraft components in icy conditions. The NASA Space Shuttle Program studied roughness as it affects augmented heating. Whether or not rough surfaces are advantageous for engineering use depends on the specific application.

Both heat transfer and skin friction are usually higher for a turbulent flow over a rough surface as

compared with an equivalent flow over a smooth surface. Recent engineering investigations have focused on the development of accurate predictive models to describe the heat transfer and fluid mechanics in turbulent flow over rough surfaces. In order to come up with such models, comprehensive sets of experimental data for a range of roughness conditions are needed. Those data sets need to include the effects of roughness geometrical shapes, sizes, distributions, and whether the roughness character is uniform or random.

The types of roughness investigated have varied, as have also the flow geometries and configuration. Machined threads, wires close to the surface, spheres, hemispheres, cones, pyramids, humps, angles, transverse bars, cylinders, half cylinders and sand grains, are some of the roughness elements that have been studied. The present study is the first to be done using castings of naturally occurring ice accretions.

The earliest studies of the roughness problem were done by Nikuradse [1933] and Schlichting [1936]. More recently, experimental work has been performed by Scaggs, Taylor, and Coleman [1988], Taylor et al. [1988], Coleman et al. [1988], Hosni, Colman, and Taylor [1991], Taylor et al. [1992], Hosni et al. [1993], Van Fossen et al. [1984] and Poinsatte [1990].

Heat Transfer Model and Testing

A technique was developed at the University of Toledo to cast frozen ice shapes that had been grown on a metal surface. The substrate consisted of a ceramic powder commercially known as 'Refracto Mix #1'. This powder is specifically designed for use in investment castings where fine detail transfer from the investment to the cast is critical. Because of the need for casting at subfreezing temperatures, the mold slurry needed to be at the same subfreezing temperatures as the ice accretions. Ethanol was eventually chosen as the most suitable fluid for the slurry. The binding agent was silica that was colloidally suspended in the ethanol. Just before pouring the slurry over an ice shape to be cast, ammonium hydroxide was added to the mix as the catalyst so that the silica binder would solidify. Once the mold cured and was baked to thoroughly dry it, molten aluminum was poured in and allowed to set. After solidification, a high pressure water jet was used to remove all traces of the mold material from the aluminum casting.

After deciding which sections of the castings the test specimens were to come from, a wire EDM machine was used to drop out the test tiles. This device was used to ensure clean cuts with no disturbance of the surface characteristics, while at the same time maintaining very close tolerances. The different types of accretions that the test tiles represented can be loosely characterized as: closely spaced rough glaze, loosely spaced rough glaze, closely spaced mildly rough glaze, smooth glaze, smooth rime, rime with small feathers and rime with very large feathers. Photographs of the actual test tiles assembled into the eight models are shown in Plates 1 through 8. The scale placed at the bottom gives a sense of perspective size in inches.

Figure 1 depicts the manner in which the heat transfer model was assembled. The model consists of two parts, the test bed and the saddle. The test bed is, in essence, a large composite of many heat flux gages and guard heaters, as can be seen in Figure 1. The test bed consists of a center row of test tiles, each being approximately 0.5 inches in the flow direction, 1.25 inches perpendicular to the flow, and 0.5 inches deep. Along the sides of these test tiles are guard tiles, four on either side, having the same roughness to ensure flow symmetry. The test tiles and side guard tiles were all instrumented with heat flux gages and thermocouples to measure and control their temperatures. This upper test surface was then epoxied to a large bottom plate outfitted with a foil heater to keep it at the same temperature as the test tiles, thus preventing downward conduction. As can be seen in Figure 1, an intermediary structure, being called the saddle, interfaces the test bed with the wind tunnel test section.

Adjustable struts mounted between the bottom of the saddle and the test section floor permitted accurate placement/alignment of the test bed. Circular disks mounted to the sides of the saddle and toward the end of the saddle fixed this end, and permitted rotation using this as a pivot point when the struts were adjusted. These circular disks were actually part of the test section's two side walls, and sat within two openings in the wall.

The front part of the saddle, as can be seen, is outfitted with a noseblock, the upper surface of which is a 10:1, one-sixteenth inch thick ellipse. This was needed to ensure a smooth uniform airflow onto the test bed. Without this, a separation bubble would form at the leading edge of the test bed, and reattach

downstream. The noseblock requires a correction associated with an unheated starting length in the thermal convective problem, but it could not be avoided.

The experiments were carried out in a dry wind tunnel that is schematically shown in Figure 2. Air drawn from the test cell passed through a flow-conditioning section and a 4.85:1 contraction before entering the 15.2-centimeter-wide by 68.6-centimeter-high test section. The maximum velocity attainable was about 46 meters/second. Clear tunnel turbulence levels were less than 0.5 percent. After leaving the test section, the air passed through a transition section into a 10-inch pipe in which a flow-measuring orifice and a butterfly valve were located. Four thermocouples around the perimeter of the inlet measured the stagnation temperature.

Steady-state operating conditions (temperatures, pressures, gage voltages and currents, etc.) were recorded on the laboratory data acquisition system called ESCORT (Miller, [1980]). An energy balance was solved to determine the Stanton number for each test tile for all of the roughness models.

A much more detailed description, with schematics, along with verification testing of the model and data analysis is presented in Masiulaniec, et. al. (1995), which is a paper on the design and verification of a heat flux based model that can be used to generate experimental plots of Stanton Number vs. Reynolds Number.

Results

The results for the eight roughness models are shown in Figures 3 through 14. Free-stream velocities at the inlet of approximately 31, 68, 107 and 155 feet per second were used. The test bed was actually held at a slight angle to the flow, so that any misalignment problems with the tunnel or in assembling the model to the saddle would not prematurely trip the boundary layer. An inspection of Plates 1 through 8 clearly shows that the roughness numbering is 6, 5, 7, 2, 3, 1, 4, and 8, where 6 is the smoothest and 8 is the roughest.

Figures 3 through 10 show the curves of Stanton Number versus Reynolds Number for the eight roughness models individually plotted for all four test velocities. As would be expected, Figure 6 showing the results for the smoothest plate has the lowest heat transfer of all 8 models. The heat transfer near the beginning takes on values close to the laminar flat plate solution, transitions, then gives values slightly higher than the turbulent flat plate solution.

As the model roughness continues to increase with models 5, 6, and 2, a similar trend is seen, but with transition occuring sooner, and the heat transfer after transition increasing as the model roughness increases.

It is interesting to note that there is essentially no change in the heat transfer results with roughnesses 3, 1, and 4. It is clear that beyond a certain level of roughness, the heat transfer is no longer a function of the roughness, but only of Reynolds Number. By carefully inspecting roughness model 2, and comparing the results with the roughness model slightly smoother (model 7), and the roughness model slightly rougher (model 3), it becomes clear that model 2 represents the critical roughness characterization beyond which the heat transfer no longer changes. Indeed, the Stanton Number curve for model 2 actually "snakes" up and down, where a series of tiles having slightly less roughness on the model approaches the curve for model 7, and where a series of tiles having a slightly greater roughness on the model approach the curve for model 3. Even though model 4 had fairly pronounced rime feathers over all of the test tiles, making the surface extremely rough, the heat transfer was still the same as in the relatively 'smoother' rough models 3 and 1.

As can be seen in Figure 10 for roughness model number 8, a Stanton Number curve was produced that was substantially higher than for roughness models 3, 1 and 4. The roughness on this model, however, was characterized by very large rime feathers. The higher Stanton Numbers are presumed to be due to enhanced heat transfer as a consequence of fin effects.

Figures 11 through 14 are composite plots of all eight roughness models at a given velocity, for each of the four velocities used in testing. By observing these four plots, it becomes very apparent that there is a family of curves where the Stanton Number gradually increases as the plate roughness increases, with model 2 representing the critical roughness beyond which the Stanton Number curves remain constant, until another heat transfer mechanism becomes important (the large rime feathers in model 8).

Concluding Remarks and Recommendations

This effort is the first attempt to provide experimental data on the convective heat transfer coefficient over ice-roughened surfaces in horizontal flight. A family of heat transfer curves has been generated as a function of model roughness. At this point, analytical work needs to be done to obtain a roughness characterization parameter from the models that were tested, so that an empirical correlation can be obtained using the test data. The experimental data obtained should provide useful information in sizing and selecting de-icing and anti-icing components to protect surfaces in horizontal flight.

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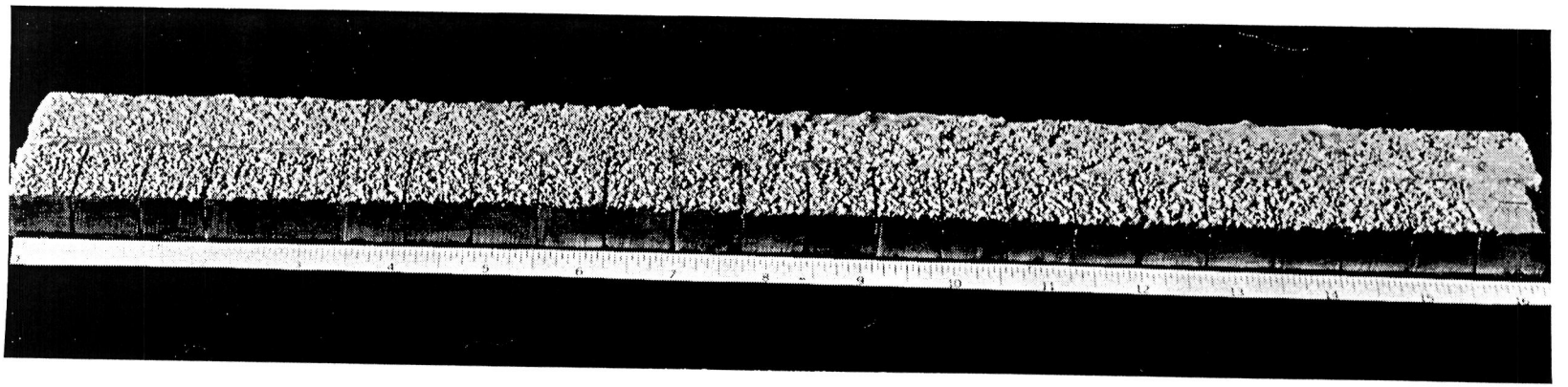

Plate 1: Perspective View of Roughness Model No. 1

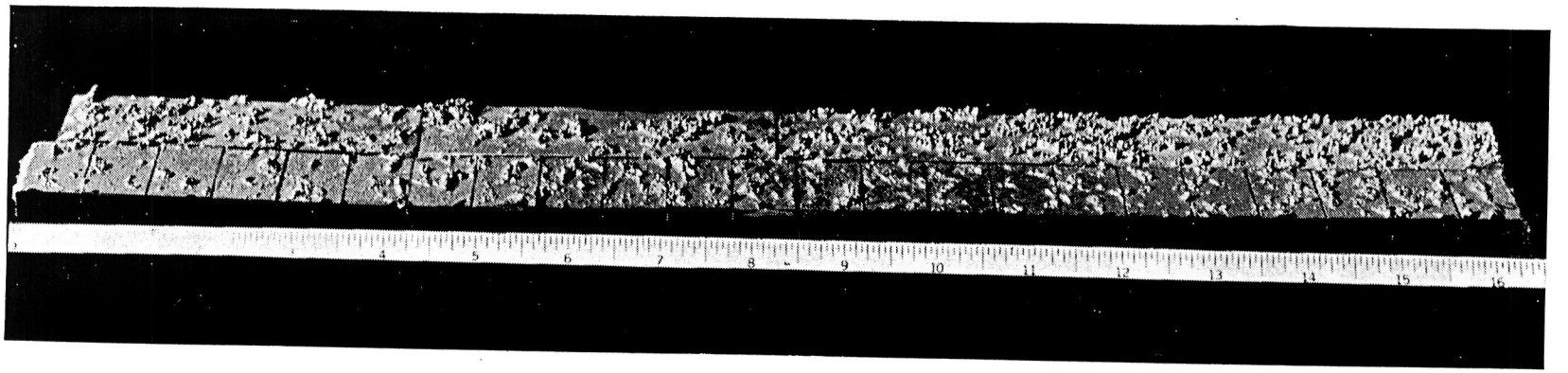

Plate 2: Perspective View of Roughness Model No. 2

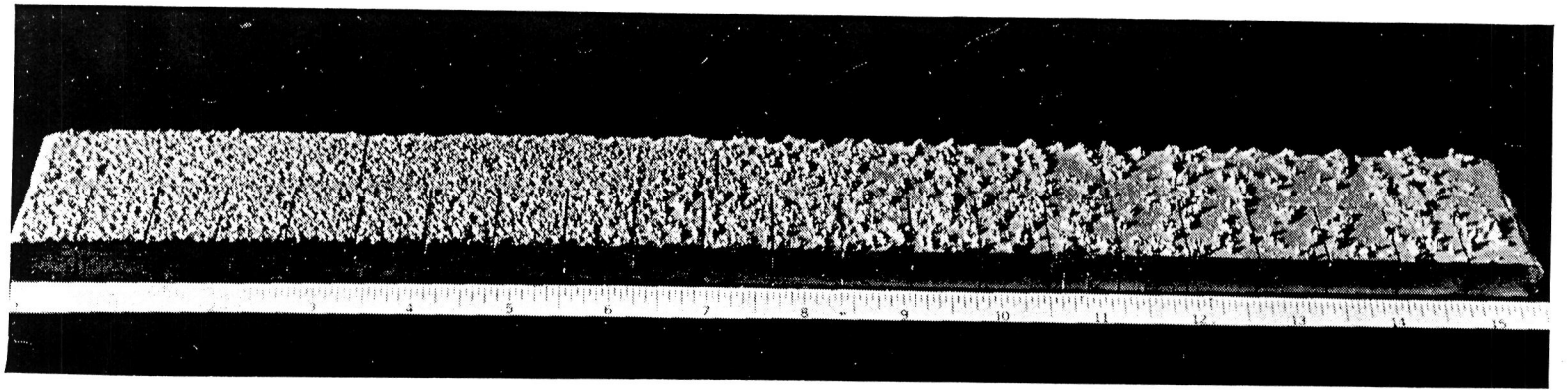

Plate 3: Perspective View of Roughness Model No. 3

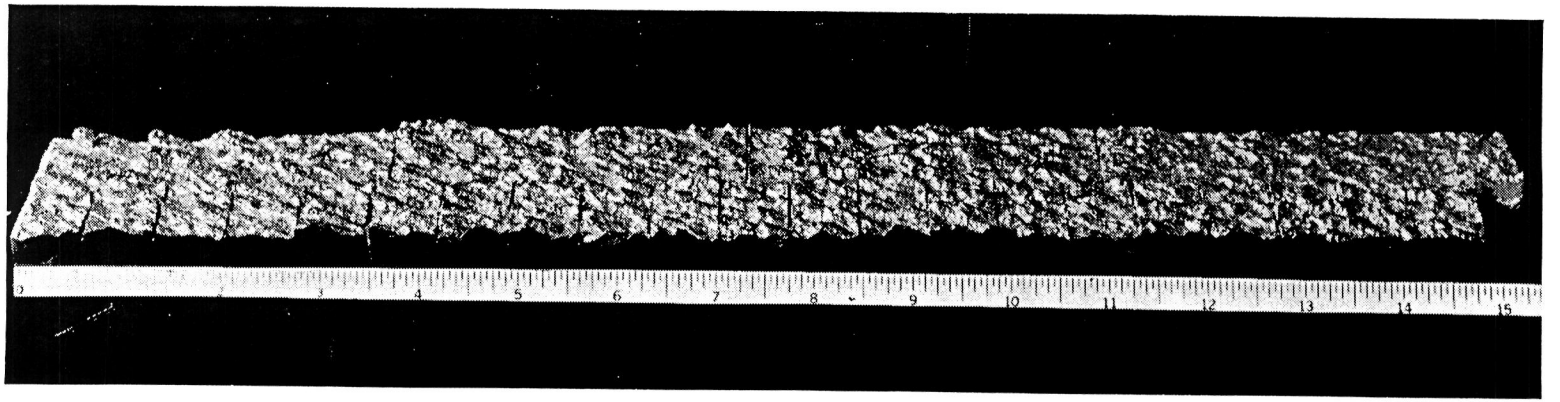

Plate 4: Perspective View of Roughness Model No. 4

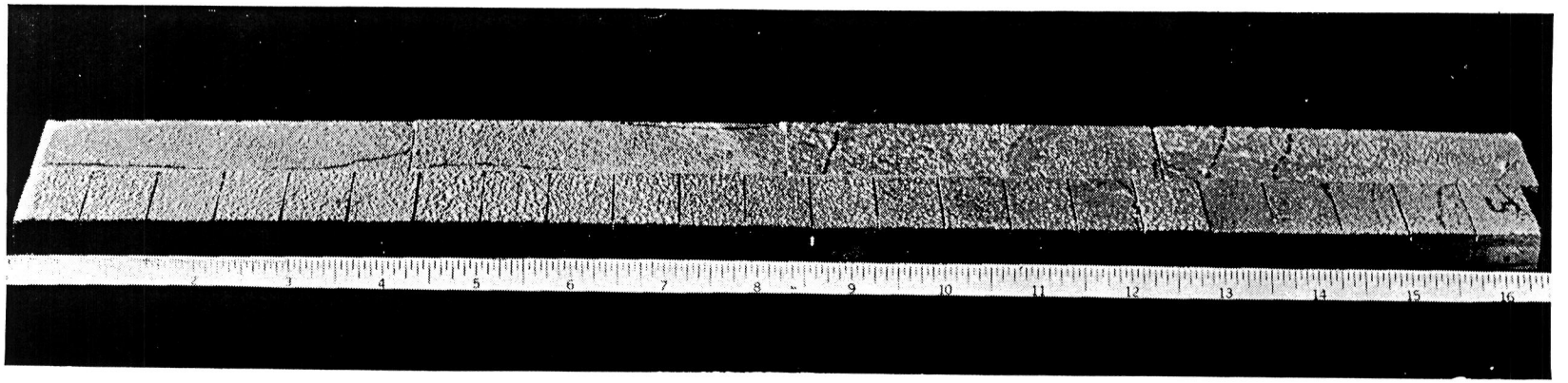

Plate 5: Perspective View of Roughness Model No. 5

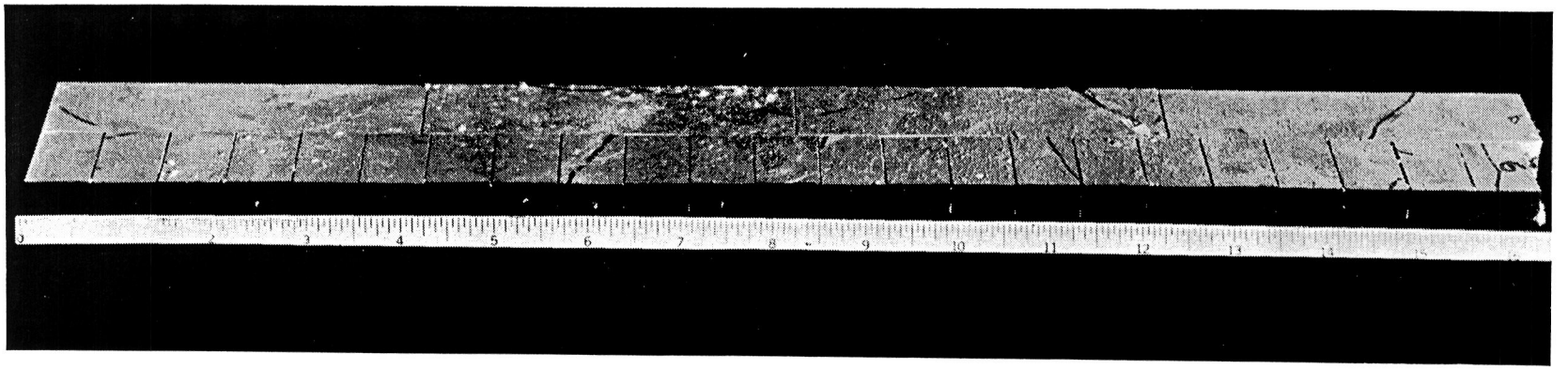

Plate 6: Perspective View of Roughness Model No. 6

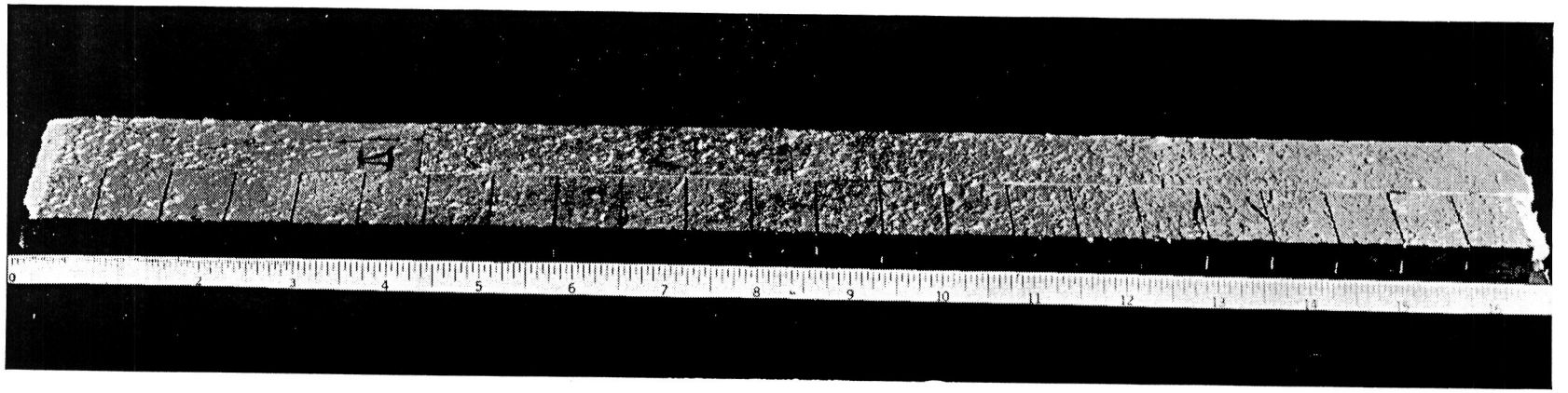

Plate 7: Perspective View of Roughness Model No. 7

Plate 8: Perspective View of Roughness Model No. 8

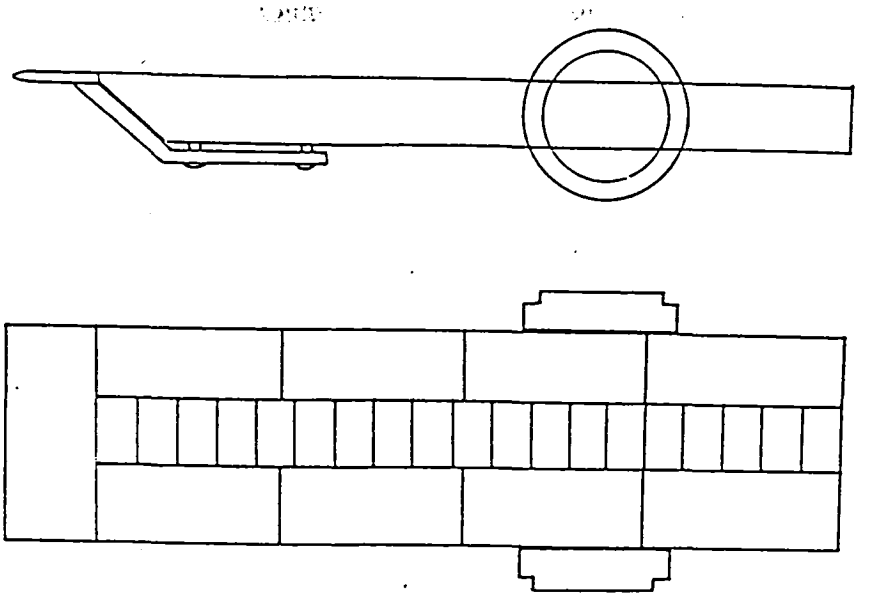

Fig. 1 Top and Side Views of Heat Transfer Model Installed in Saddle.

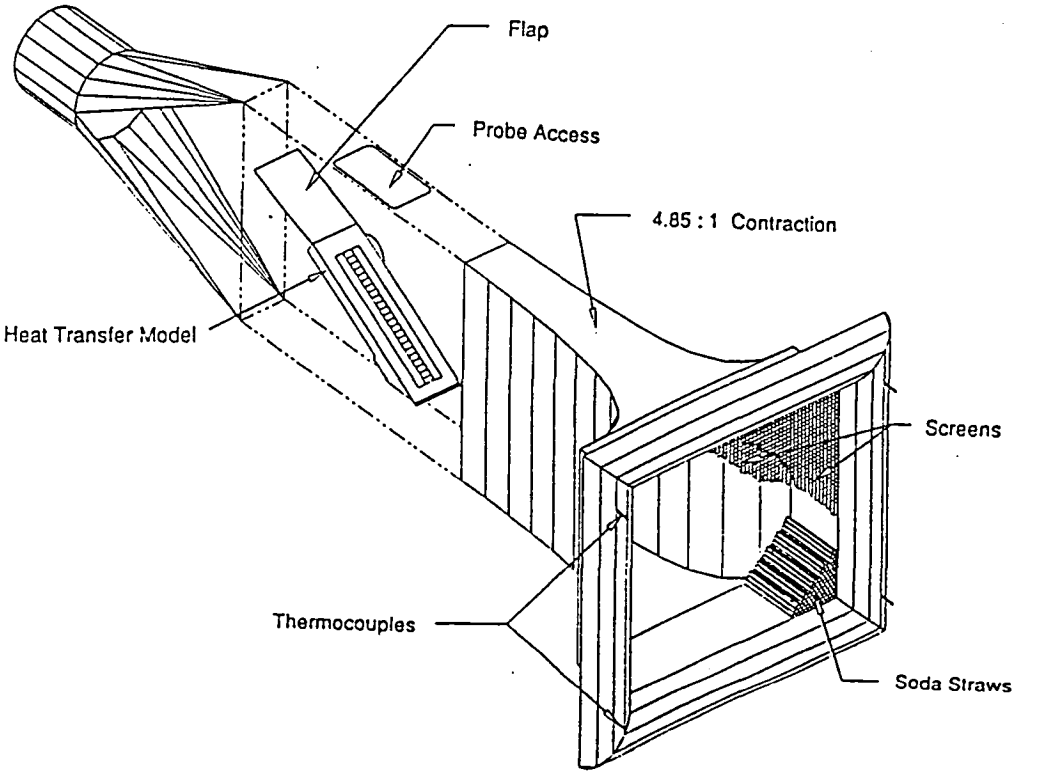

Fig. 2 Schematic of Wind Tunnel with Heat Transfer Model Installed.

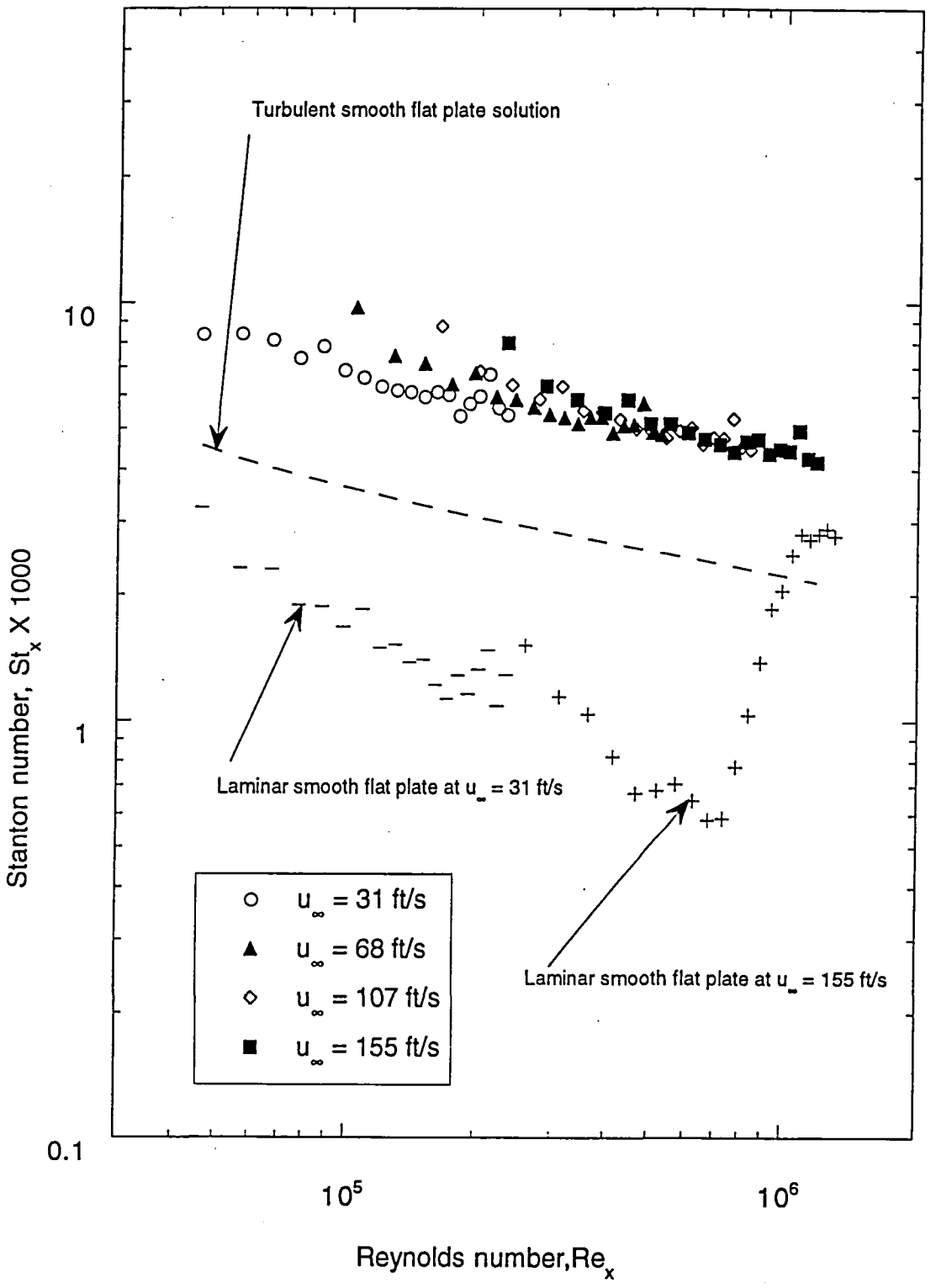

Fig. 3 Stanton number vs. Reynolds number. Rough horizontal plate no. 1 at different free-stream velocities.

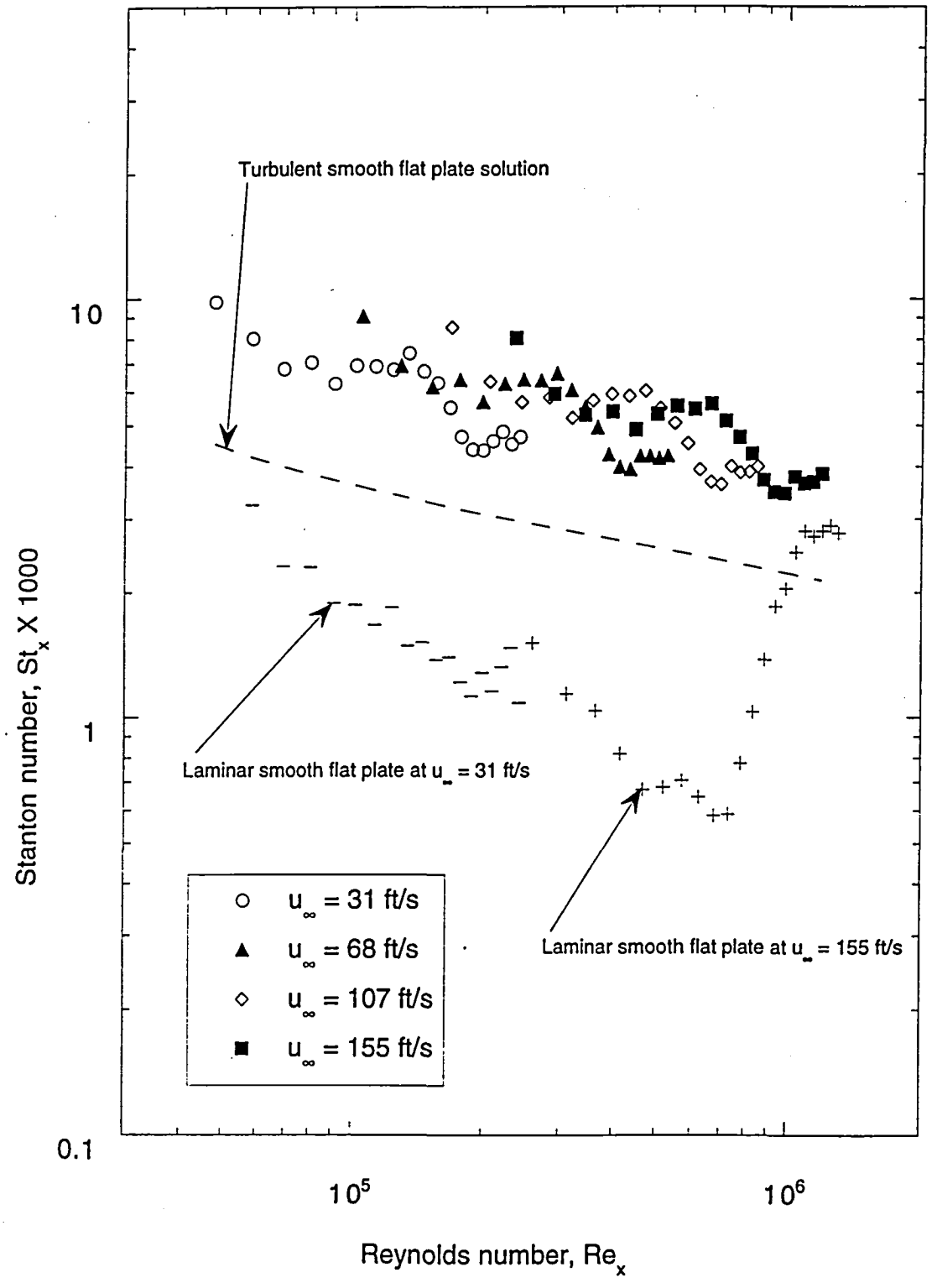

Fig. 4 Stanton number vs. Reynolds number. Rough horizontal plate no. 2 at different free-stream velocities.

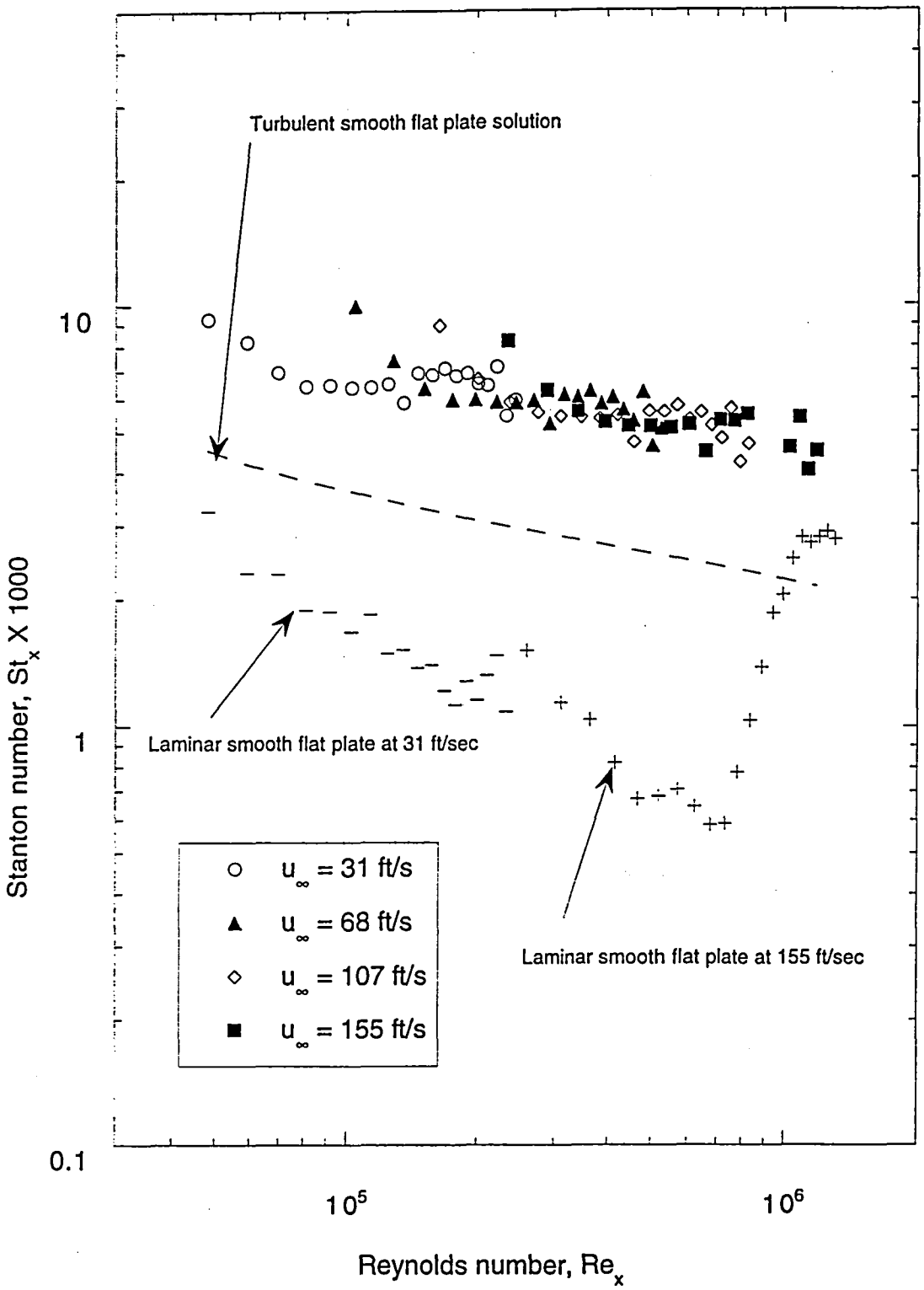

Fig. 5 Stanton number vs. Reynolds number. Rough horizontal plate no. 3 at different free-stream velocities.

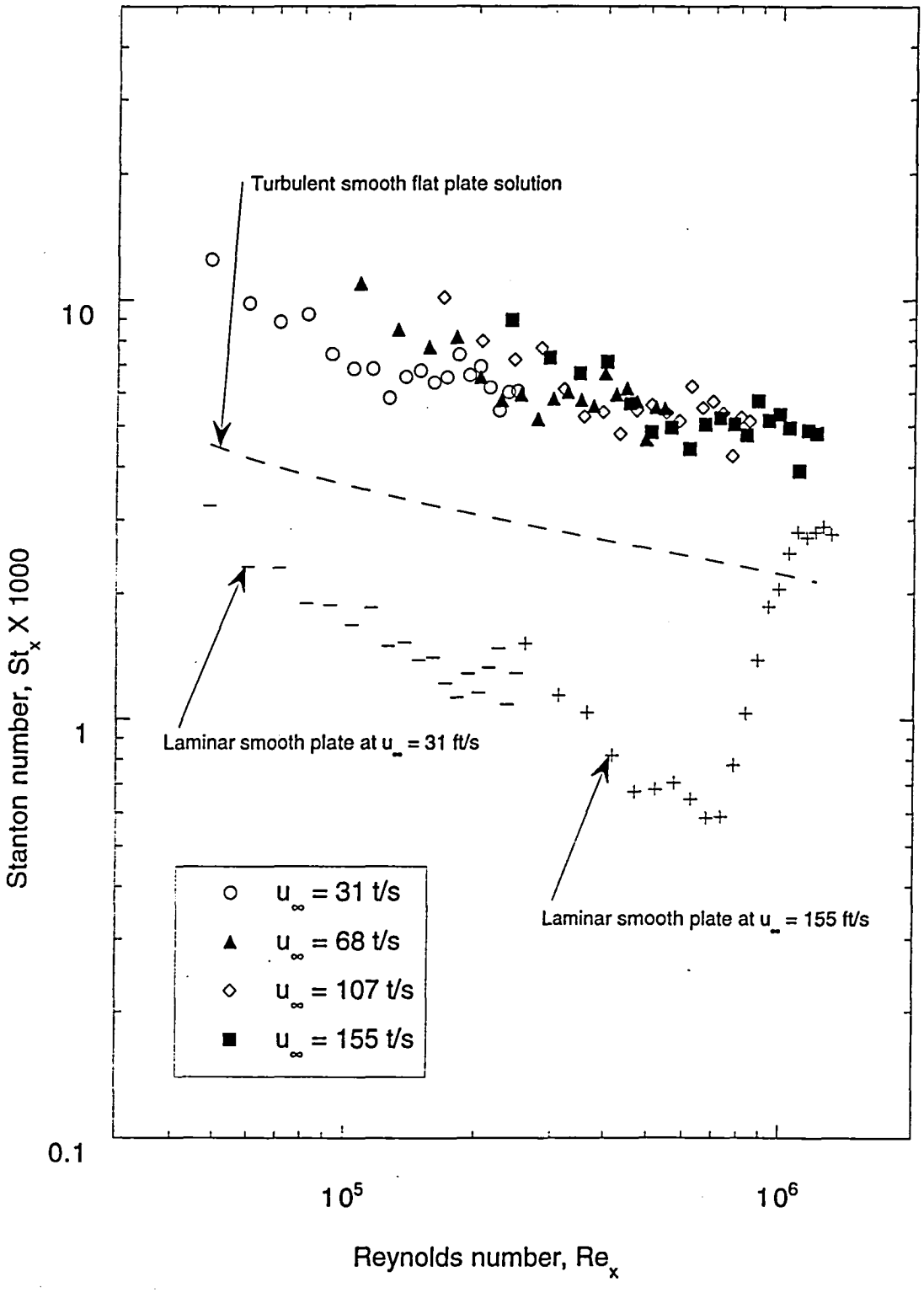

Fig. 6 Stanton number vs. Reynolds number. Rough horizontal plate no. 4 at different free-stream velocities.

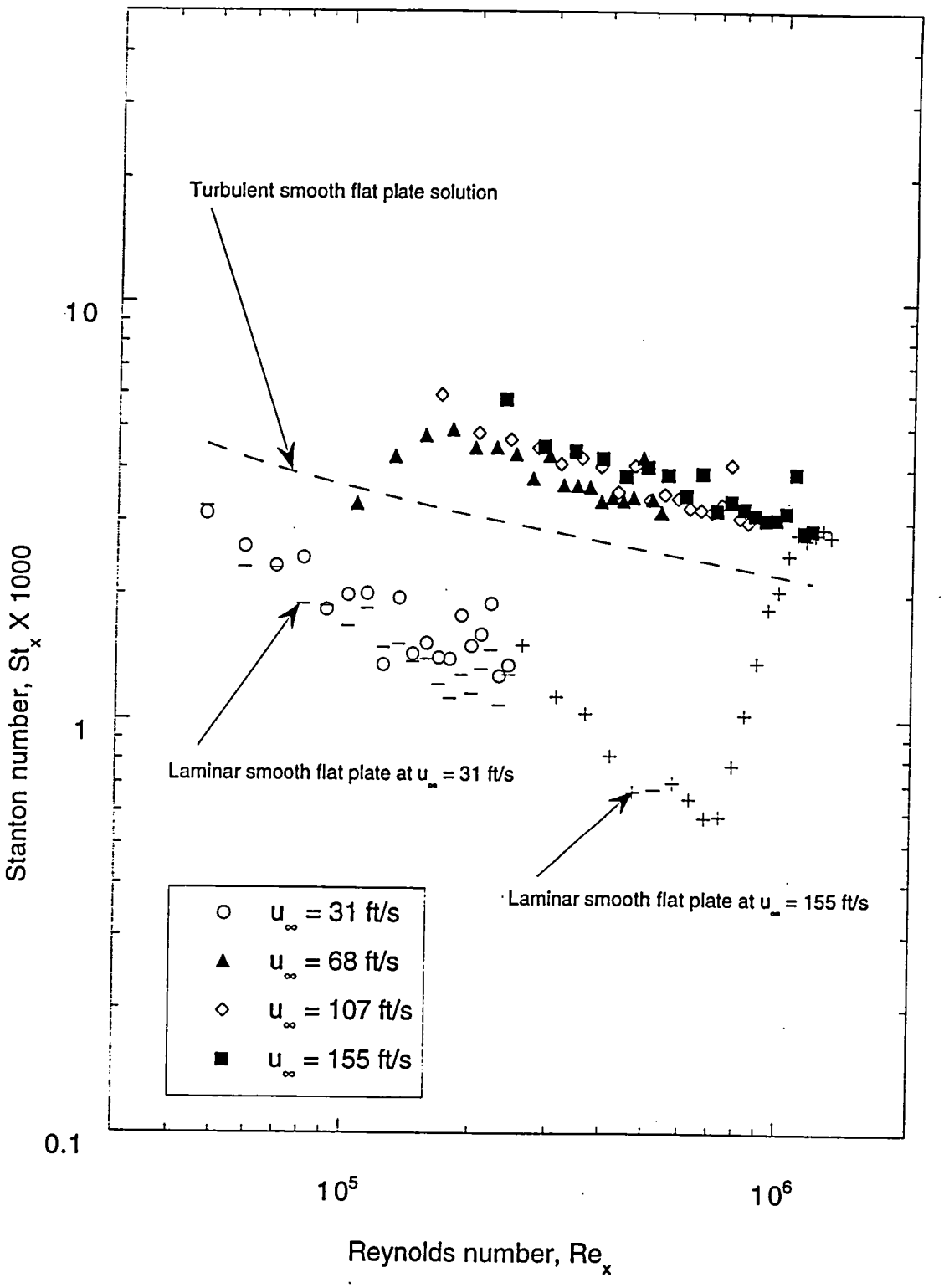

Fig. 7 Stanton number vs. Reynolds number. Rough horizontal plate no. 5 at different free-stream velocities.

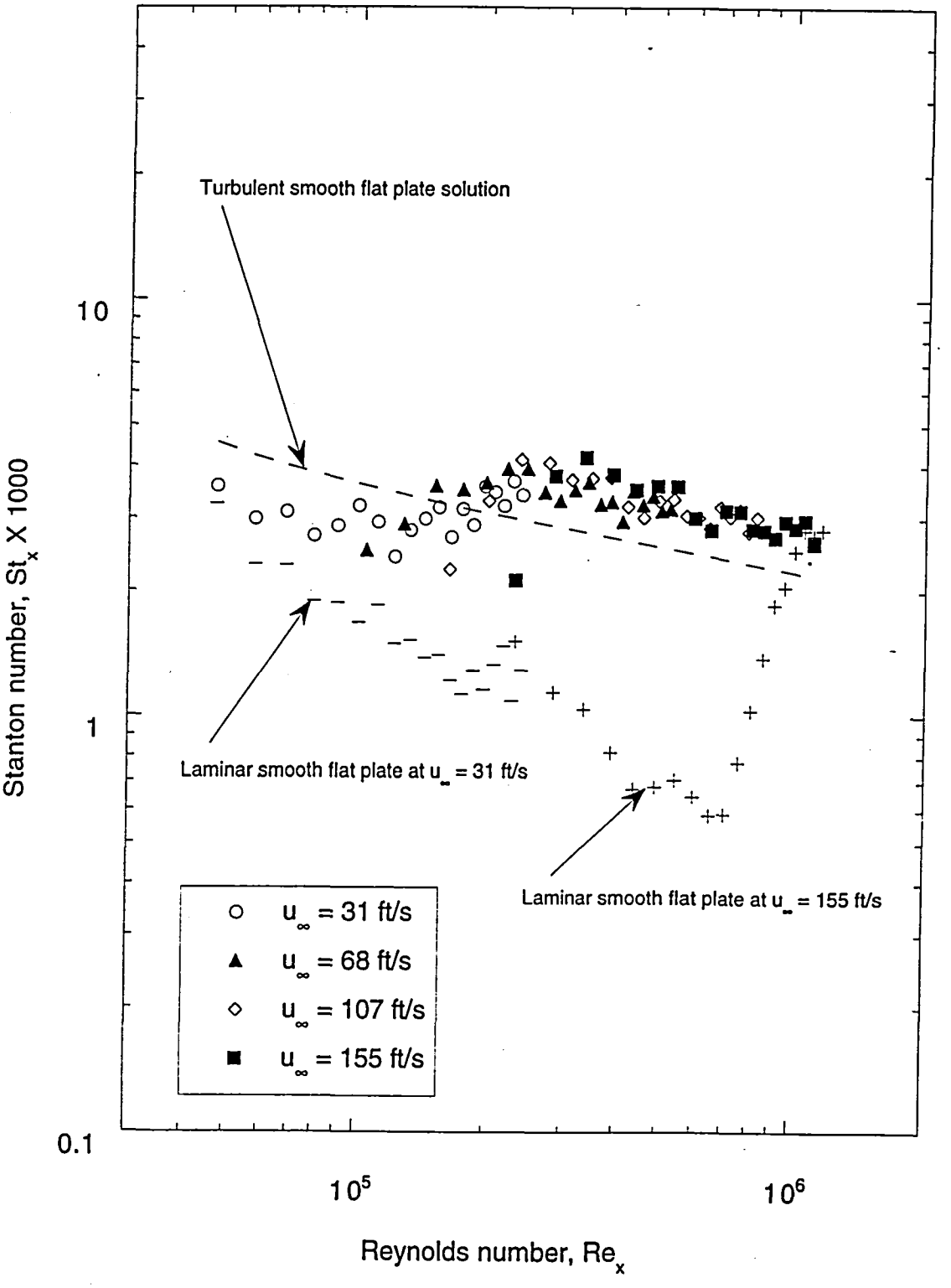

Fig. 8 Stanton number vs. Reynolds number. Rough horizontal plate no. 6 at different free-stream velocities.

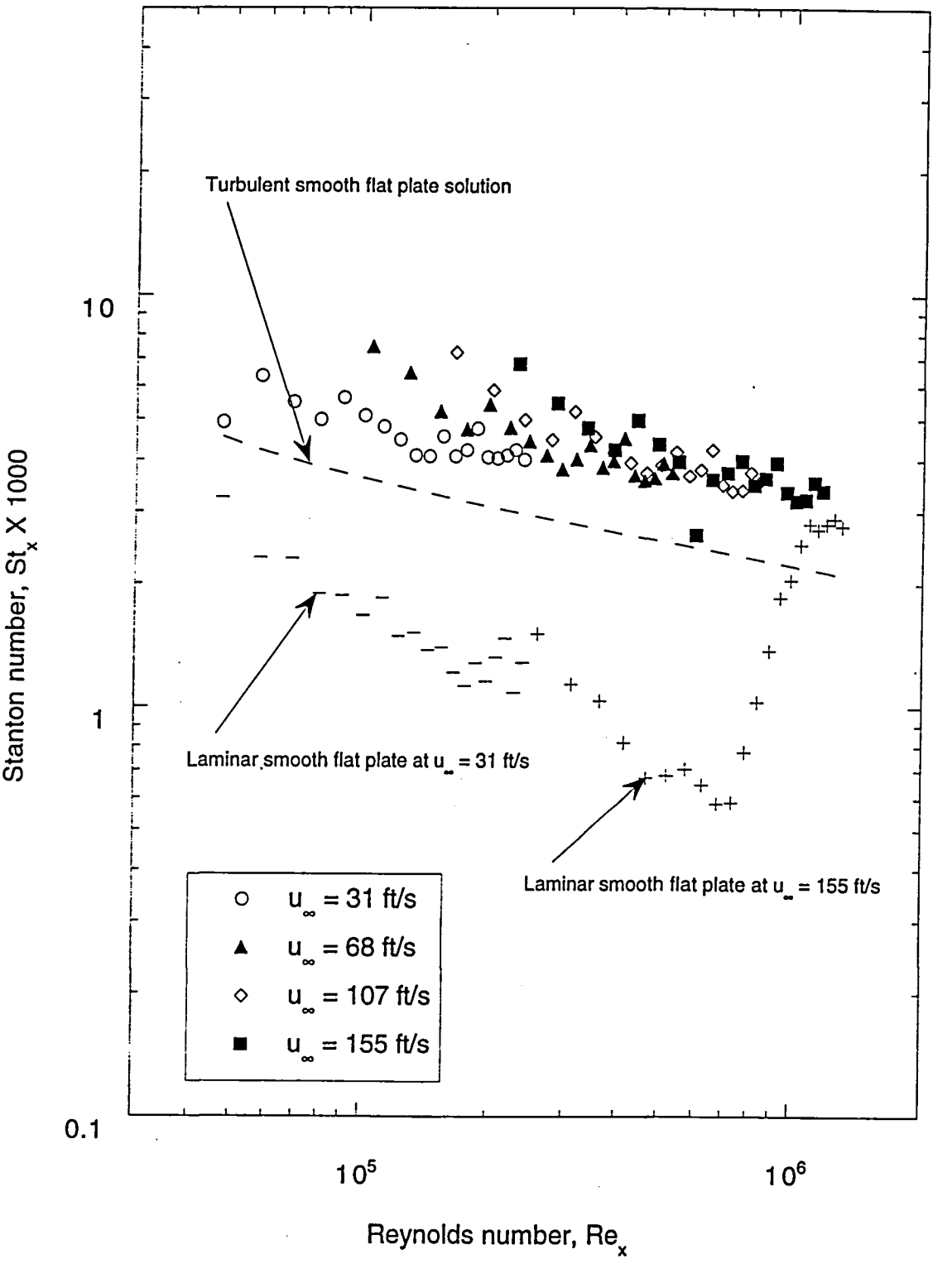

Fig. 9 Stanton number vs. Reynolds number. Rough horizontal plate no. 7 at different free-stream velocities.

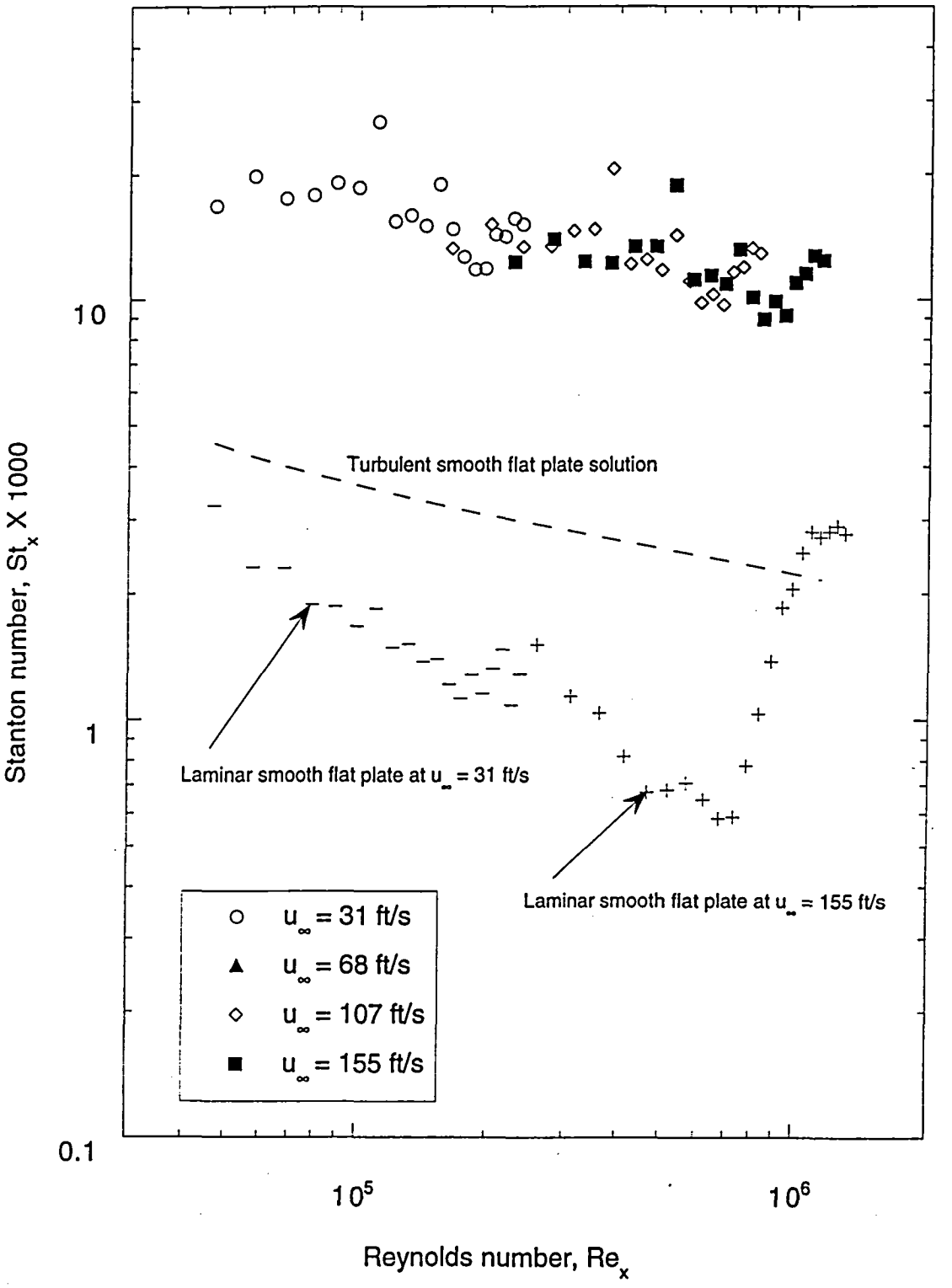

Fig. 10 Stanton number vs. Reynolds number. Rough horizontal plate no. 8 at different free-stream velocities.

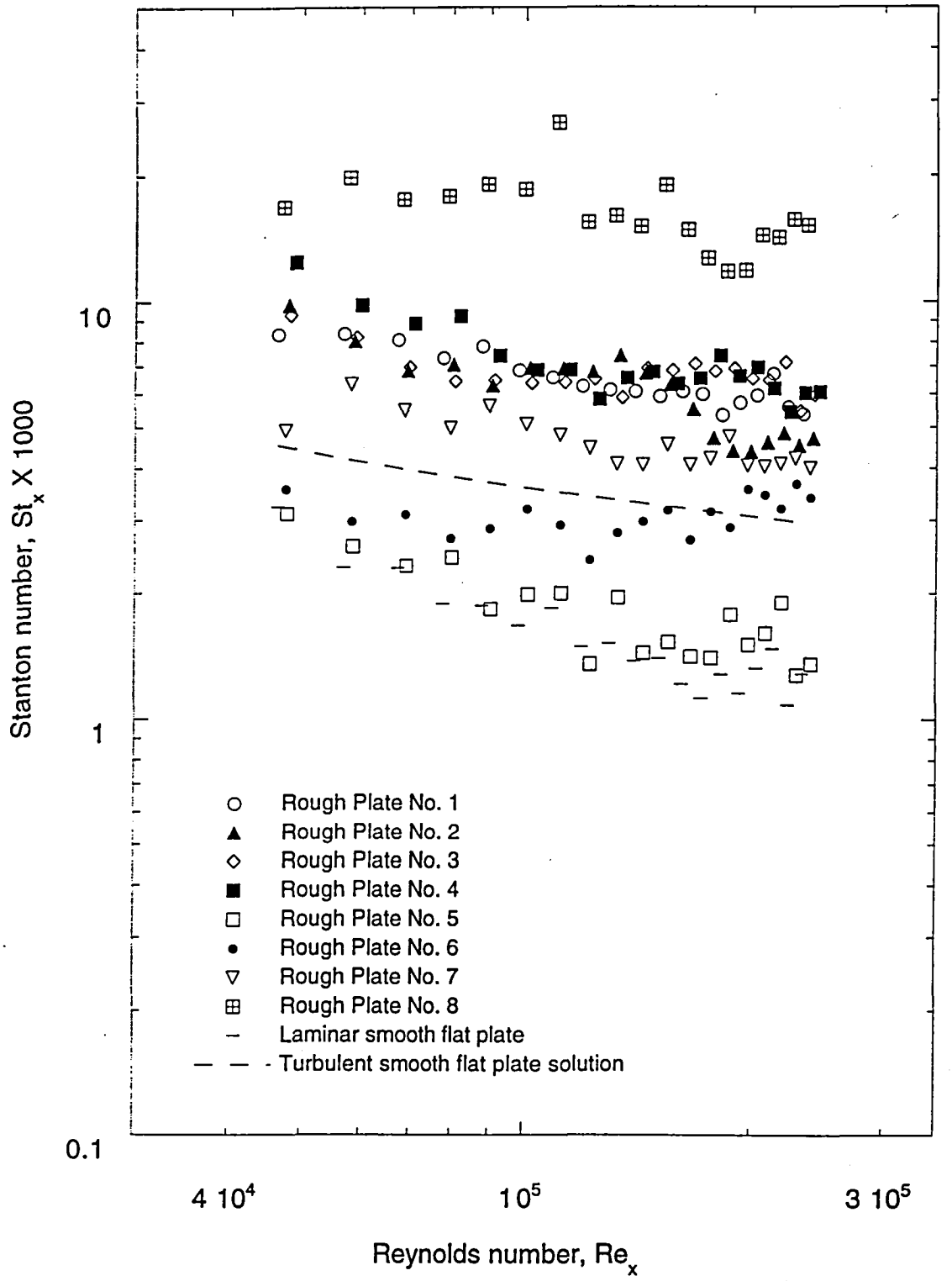

Fig. 11 Stanton number vs. Reynolds number. Comparison of rough plates at u_∞ = 31 ft/s.

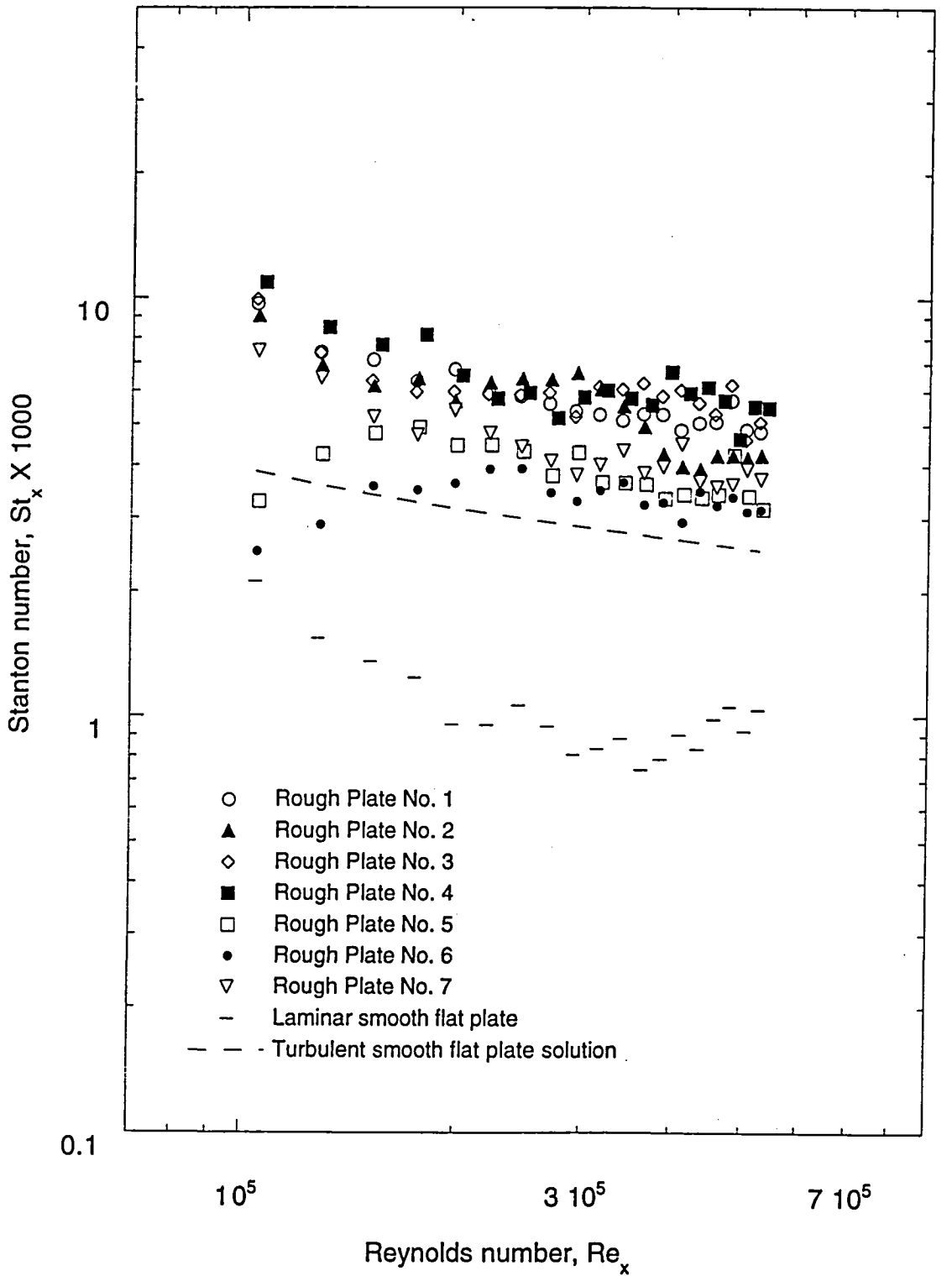

Fig. 12 Stanton number vs. Reynolds number. Comparison of rough plates at u_∞ = 68 ft/s.

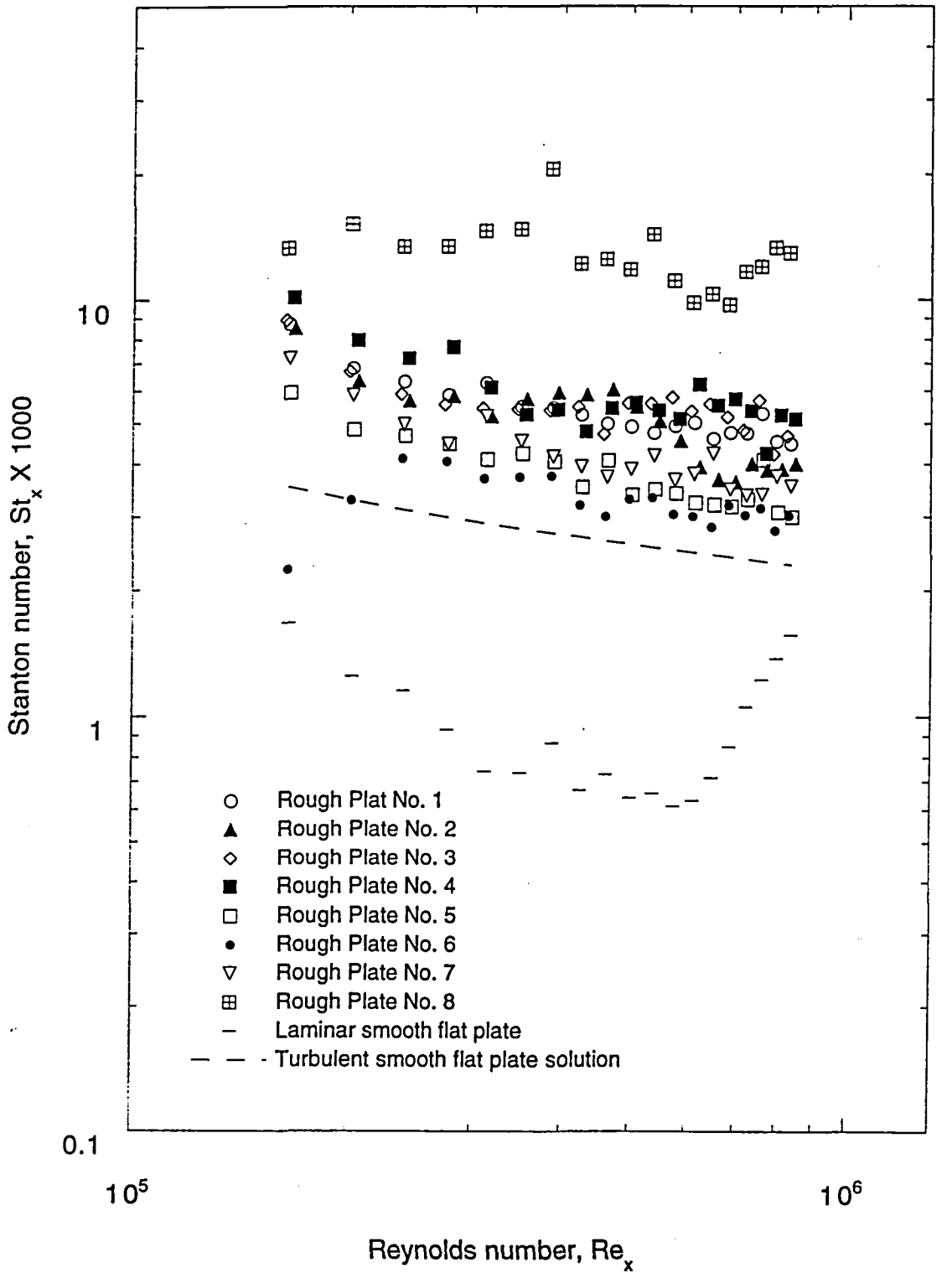

Fig. 13 Stanton number vs. Reynolds number. Comparison of rough plates at u_∞ = 107 ft/s.

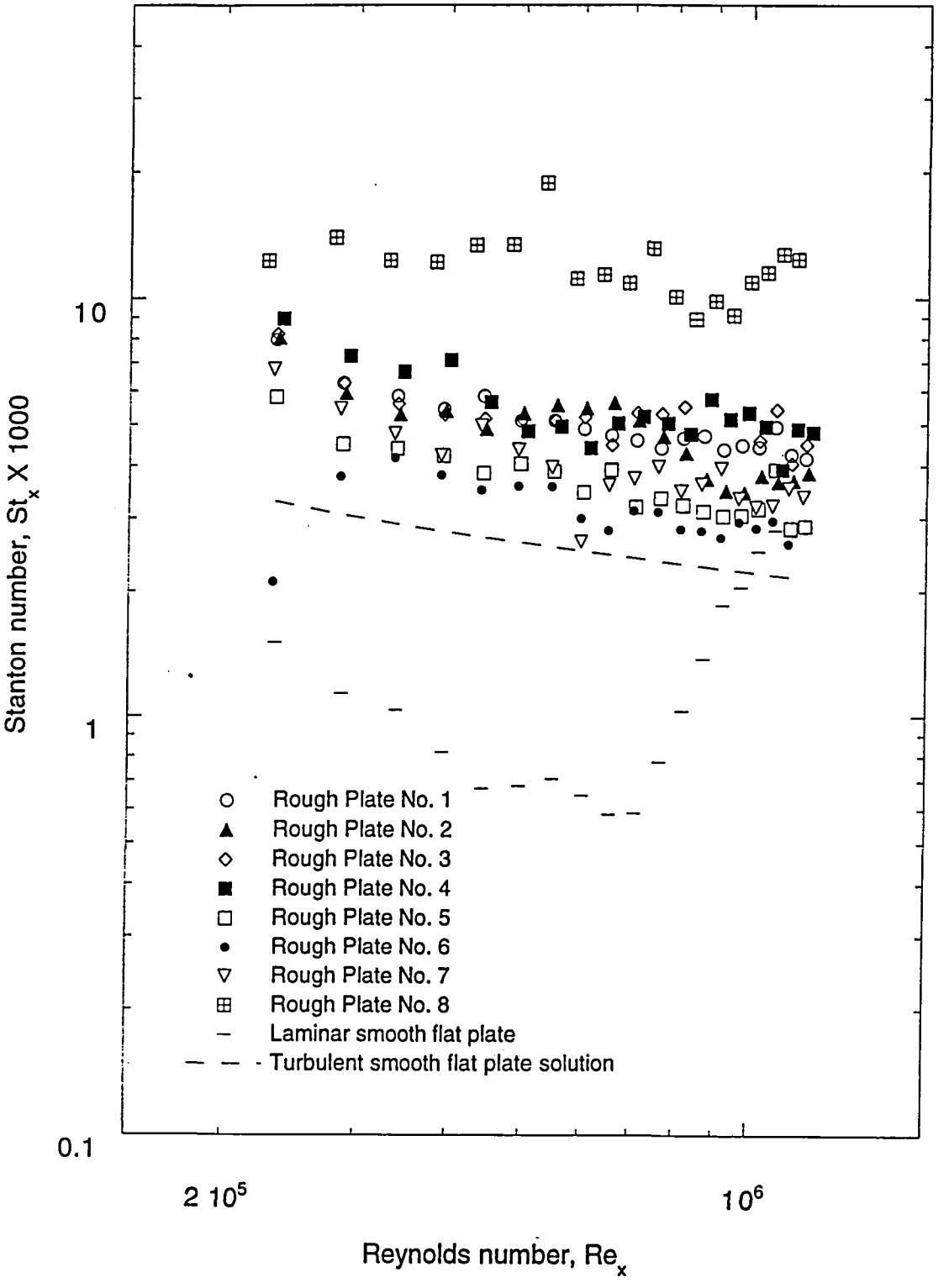

Fig. 14 Stanton number vs. Reynolds number. Comparison of rough plates at u_∞ = 155 ft/s.

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13. ABSTRACT (*Maximum 200 words*)

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