Flow Visualization Studies of Free Convection Laminar-to-Turbulent Transition along a Heated Vertical Plate in Water Induced by Two-Dimensional Forced Disturbances*

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1. Introduction

The transition from laminar to turbulent flow is currently being extensively studied. However, the complexity of the three-dimensional transition phenomena as well as the still limited possibilities of a complete mathematical treatment are leaving many open questions.

In the Institute of Applied Mathematics and Mechanics of the DFVLR in Freiburg problems of the mechanism of boundary layer instability and transition have been studied mainly theoretically. Some experimental investigations of laminar-to-turbulent transition phenomena of the boundary layer along a vertical heated plate in water and air have also been made. The experimental findings of ECKERT, SOEHNGEN and SCHNEIDER [1] that the laminar-to-turbulent transition of the boundary layer flow along a vertical plate in free convection bears a great similarity to the transition phenomena of a Blasius boundary layer on a flat plate, as well as the relative simplicity of the experimental set-up, have been the main cause for our decision to begin the investigations [2, 3]. In the course of the experiments and as more experimental and theoretical papers on free convection instability along a heated vertical plate have been available [4 to 11], it has become evident that the free convection transition phenomena are considerably more complicated than those occurring in the Blasius boundary layer. No theoretical three-dimensional instability investigation for the case of the free convection flow along a heated vertical plate has been published so far. A cautious comparison with the instability development occurring in the early transition stage of the Blasius boundary layer remains therefore the only approach possible, at present. This applies especially to the observed interaction effects of Tollmien-Schlichting waves with longitudinal vorticity [12, 15, 16], and to the occurrence of shear layer concentrations [13, 14].

The present paper will review some of the results of visualization studies of forced transition of a free convection boundary layer along a heated vertical plate in water, induced by two-dimensional forced disturbances, supplementing the experiments in natural transition in water [2]. Special attention will be paid to the occurrence of longitudinal vorticity and concentrated shear regions.

The study of boundary layer transition induced by controlled forced disturbances enables a better understanding of the phenomena by overruling the random natural disturbances of the inflow to the boundary layer along the vertical plate.

2. Experimental Set-up

The experiments were conducted in the same water tank and with the same plate as in [2], additionally equipped with two-dimensional disturbance generators. The electrically heated hollow brass plate of 200 mm
width, 600 mm height and 9 mm thickness was sus-
pended in a glass water tank of 470 × 470 mm cross-
section and 1200 mm height (Fig. 1). The plate was
painted black. The temperature of the plate could be
varied up to 20 °C over the water temperature. Plain
tap water was used.

The ribbon oscillations were produced mechanically
(Fig. 1) by a linkage system driven by a cam of
variable eccentricity. The ribbon frequency, amplitude,
and distance from the wall could be controlled re-
motely. Phosphor bronze ribbons of 0.05 mm thick-
ness and of 4 and 8 mm width were used. The vibrating
ribbon was located 175 mm from the leading edge of
the plate and spanned its entire width.

The pulsed wire also spanned the entire plate width.
Its distance from the plate surface and from the leading
dge could be varied. Platinum wire ranging from
0.025 to 0.1 mm in diameter was used.

5. Observed Forced Transition Flow Development

The boundary layer flow development in free con-
vection under two-dimensional forced disturbances
may, according to visual observation be divided into
the following stages:

I. Undisturbed laminar flow.

II. Nearly two-dimensional Tollmien-Schlichting
waves developing behind the operating disturbance
generator which was always located in the zone of
amplification.

III. The Tollmien-Schlichting waves continue to
be amplified, the first signs of three-dimensionality
begin to appear: sidewise meandering motion of the
streamlines and warping of the wave fronts.

IV. The three-dimensionality continues to grow. In
visualization with aluminum lamellae, first signs of
spanwise periodical shear concentrations appear far
from the wall and also nearer to the wall as brighter
spots, containing a large amount of light traces of
greater intensity.

V. Depending on the Pr and Gr numbers, the plate
temperature, the forced disturbance amplitude and
frequency and the general turbulence degree of the
inflow to the boundary layer along the plate, the
two shear concentration zones continue to develop and
to intensify. In the shear zone in the outer part of the
boundary layer discrete longitudinal vorticity concen-
trations begin to appear with a downward plunging
tendency. They intensify, reach a maximum, slow down
and disintegrate. These disturbances have now extended
far beyond the thickness of the original non-disturbed
boundary layer, destroying the regularity of the inflow.
As a secondary effect, the transition close to the wall
is also influenced.

1 At y ~ 0.35 -- 0.45 σ, where σ is the boundary layer thickness,
defined as the value at which the velocity u has dropped to one
percent of Umax, and y is the distance from the wall.
2 At y ~ 0.08 -- 0.15 σ.
3 The more intense light reflection and formation of streaks
are produced by the orientation property of aluminum lamellae. In flow
of no shear or of not very strongly developed shear, the aluminum
lamellae retain their random space orientation so that only a very
small percentage of them is able to reflect the light towards the
camera. The percentage of reflecting lamellae suddenly increases
when the lamellae take a statistically preferred orientation towards
the direction of the maximum shear. This enables a visualization of
zones of concentrated shear and, due to the lateral illumination, also
of longitudinal vorticity concentrations and longitudinal vortices
(cf. [18] and [2], pp. 15/18).