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# Convective heat transfer increase in internal laminar flow using a vibrating surface

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ABSTRACT

Laminar to turbulent transition is a very complex phenomenon, where instability waves are able to grow inside the fluid boundary layer. According to the receptivity theory, only some perturbations with particular frequencies are able to induce those instability waves. The aim of this paper is to find a new way to increase the convective heat transfer by a locally promotion of those instability waves. This is obtained with the introduction in a laminar water flow of small pressure disturbances in a laminar water flow. Experiments have been performed in a close circuit water tunnel. A stack of two piezo-ceramic actuators (M.E.M.S.) has been used to induce vibration on a circular surface located on the tunnel floor. The vibration effect has been evaluated by monitoring the heat transfer coefficient on a heated circular pin-fin. The pin has been positioned downstream of the vibrating surface and equipped with calibrated thermocouples. Tests have been performed at different Reynolds numbers, pressures and water temperatures. The results have showed an increase in Nusselt number of up to 9.33%. Flow visualizations with dye have been reported to better understand the phenomenon.


## 1. Introduction

In electronics and micro-electronics applications the highest heat transfers coefficients are obtained through liquid cooling using cold plates and pin-fins. In these applications cooling performances depend on the fluid thermal properties, the geometry and number of fins (Montelpare and Ricci [1]) and the flow regime. Turbulent flows have higher heat transfer coefficients but laminar flows are sometimes used to reduce pressure drops and noise.

A simple and very common way to increase convective heat transfer in a laminar flow is to introduce obstacles, namely turbulators, in the flow field. These obstacles induce a turbulent flow that enables a greater heat exchange, although on the other hand, they bring more pressure drops. The present study is aimed at analyzing a new technique which is able to increase the convective heat transfer coefficient of liquid cooled short pin fins. The basic idea is to mechanically promote local transition to turbulence in the incoming laminar flow by introducing spot flow disturbances in the upstream channel walls. The pressure disturbances are generated by membrane vibrations imposed by an M.E.M.S. actuator. This technique may increase the pin thermal exchange on demand but it does not induce further pressure drops when the M.E.M.S. actuator is off.

Transition from laminar to turbulent flow is a complex mechanism that can be divided into three main parts: boundary layer receptivity, linear amplification stage and non-linear amplification stage. If these disturbances have a suitable frequency and amplitude, they could be accepted by the flow field and induce instability waves inside the boundary layer. Downstream of the zone disturbed, the instability waves are damped by the stable nature of the flow and re-laminarization occurs. This behavior is described in the receptivity theory and is the first of the three parts in which the transition to turbulence process can be divided. The receptivity theory describes how perturbations of particular frequencies are able to create instability waves inside the boundary layer; these waves are named Tollmien–Schlichting Waves (TS waves). The concept was first introduced by Morkovin [2], and then investigated theoretically and experimentally in several studies; Kachanov [3], Bake et al. [4], Ivanov et al. [5] could be read for more details. The second part deals with the linear amplification of the TS waves. This phenomenon is governed by the Orr–Sommerfeld equations (OSE). It was studied using the linear stability theory by

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**Nomenclature**

| | |
|---|---|
| $A$ | pin external surface [m$^2$] |
| $D$ | channel hydraulic diameter [mm] |
| $d$ | pin diameter [mm] |
| $f$ | vibration frequency [Hz] |
| $H$ | channel height [mm] |
| $h$ | convection heat transfer coefficient [W/m$^2$ K] |
| $k$ | thermal conductivity [W/m K] |
| $L$ | channel width [mm] |
| $\dot{m}$ | flow rate [kg/s] |
| Nu | Nusselt number |
| $P$ | water pressure [bar] |
| $Q$ | volumetric flow rate [l/min] |
| Re | Reynolds number |
| $S$ | channel cross section [mm$^2$] |
| $T$ | temperature [°C] |
| TC | thermocouple temperature [°C] |
| TR | RTD temperature [°C] |
| $t$ | student-$t$ parameter |
| $u$ | mean flow velocity [m/s] |
| $W$ | power supply provided to pin [W] |
| $w$ | weight factor |

*Greek*

| | |
|---|---|
| $\nu$ | water cinematic viscosity [m$^2$/s] |
| $\sigma$ | standard deviation |
| $\theta$ | temperature gap [°C] |

*Subscripts*

| | |
|---|---|
| 0 | absence of vibration ($f = 0$) |
| $i$ | sample index |
| film | film conditions |
| PIN | related to pin |
| $\infty$ | related to water |
| max | point of maximum effect |

Tollmien [6]; Schlichting [7] and experimentally confirmed by Schubauer and Skramstad [8]. This theory, reviewed in Schlichting and Gersten [9]; Mack [10], shows how small amplitude oscillations of velocity and pressure may grow, decay, or remain constant in time and space (stability). The last part deals with the non linear amplification of the TS waves that lead to the formation of three-dimensional vortex spots, the Λ-shaped vortexes, which drive the flow to a sudden breakdown to turbulence (Schubauer and Klebanoff [11]). This transition mechanism was first shown by Klebanoff et al. [12], who introduced three dimensional perturbations generated by a vibrating ribbon in a field of TS waves over a flat plane. A representation of this process over a flat plane is shown in Fig. 1. There is wide literature on these topics; for some insights on theory and applications, the authors point out [13–16] on boundary layer transition [17–21], on stability and receptivity and [22,23] on non dimensional analysis. According to the scheme described, the introduction of pressure or velocity disturbances with a particular frequency makes it possible to control the transition process. This has been successfully achieved in several studies based on air flows, such as [24–31]. The application of the technique in liquid cooling could be an innovative way to increase the thermal dissipation where energy consumption and noise emission are important issues. The technique could be used also in HPC or heat sinks as an emergency solution in case of critical temperature conditions, e.g. hot spots in electronic devices.

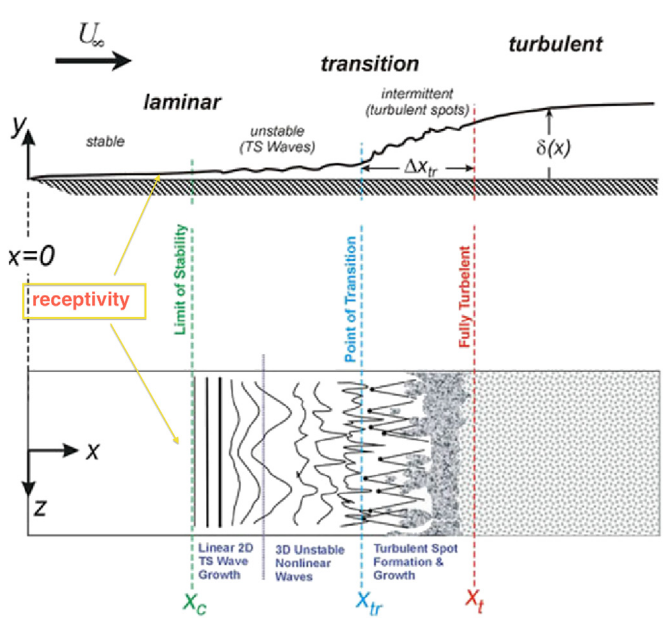


**Fig. 1.** Scheme of the transition to turbulence process over a flat plate.

The paper describes experiments carried-out in a closed circuit water tunnel on a stable laminar flow. The test section is rectangular: this geometry is very common in applications such as compact heat transfer exchangers, cooling of microelectronics components, cold plates and pin-fins systems. The Reynolds number (Re) and the channel aspect ratio (AR) are the main parameters in flow stability for rectangular ducts. Numerical investigations in Tatsumi and Yoshimura [32] suggest AR = 3.2 as the limit for stable flows. Direct measurements in Kao and Park [33] give a critical Reynolds number of 2600 for AR = 8. In the present work, tests have been performed in a rectangular section of AR = 3.17 at Reynolds numbers lower than 2500. The experimental apparatus is fully described in Chapter 2. The results in terms of Nusselt number variation are shown in Chapter 3 and flow visualizations are reported in Chapter 4.

## 2. Experimental procedure

### 2.1. Experimental facilities

The experimental investigations were performed in a closed-circuit water tunnel at the Department of Industrial Engineering and Mathematical Sciences, Università Politecnica delle Marche (DIISM). The test section is a rectangular shaped channel. The channel is made of Lexan, a transparent polycarbonate, while the floor is made of aluminum. The section is 38 [mm] wide ($L$) and 12 [mm] high ($H$), so the channel aspect ratio $L/H$ is 3.17. The hydraulic diameter $D$, defined as $D = 2S/(L + H)$, is 18.2 [mm].

The disturbance source and the heat transfer measurement system are located in the test section. The former is a vibrating circular membrane acting on the channel floor (it is described in Section 2.2). The latter is an instrumented cylinder (pin-fin) described in Section 2.4. The test section is shown in Fig. 2(a), while Fig. 2(b) describes the experimental scheme. Upstream of the test section there is a boundary layer developing channel. Two nozzles are located at the ends of the developing channel and the test