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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Numerical Investigation of Hydrodynamic and Thermal Boundary Layer Flows over a Flat Plate and Transition Control

Düz Bir Plaka Üzerindeki Hidrodinamik ve Isıl Sınır Tabaka Akışının Sayısal Olarak İncelenmesi ve Geçiş Kontrolü

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Abstract
In this study, Computational Fluid Dynamics (CFD) calculations are performed with ANSYS-Fluent for an external flow over a flat plate under constant surface temperature conditions. By using an Active Flow Control (AFC) method, the flat-plate is heated to manipulate the transition region. Calculations are performed for a steady and turbulent flow at 15 m/s free-stream velocity. Local skin friction coefficient and local heat transfer coefficient distributions along the flat-plate are investigated for laminar and turbulent boundary layers at various constant surface temperatures. For laminar and turbulent flow boundary layer characteristics, theoretical correlations in the literature are used to verify the numerical results. Results show that theoretical correlations are highly consistent with CFD results only in the laminar and turbulent regions and it is also shown that transition can only be predicted by CFD simulations. On the other hand, heating as an AFC method is found to be useful in delaying transition regime over a flat plate.
Keywords: CFD, Forced Convection, Boundary Layer Flow, Active Flow Control, Transition Region Delay

Öz
Bu çalışmada, düz bir plaka üzerindeki bir dış akış için sabit yüzey sıcaklığı koşulları altında ANSYS-Fluent yazılımı kullanılarak Hesaplamalı Akışkanlar Dinamiği (HAD) hesaplamaları yapılmıştır. Bir Aktif Akış Kontrolü yöntemi olarak ısıtma, düz plaka geçiş bölgesini manipüle etmek için kullanılmıştır. Hesaplamalar, 15 m/s serbest akım hızında daimi ve türbülanslı bir akış için yapılmıştır. Düz plaka boyunca yerel sürtünme katsayısı ve yerel ısı transfer katsayısı dağılımları çeşitli sabit yüzey sıcaklıklarında, laminer ve türbülanslı sınır tabakaları için incelenmiştir. Laminer ve türbülanslı akış sınır tabakası karakteristiklerinin doğrulanması için literatürdeki teorik korelasyonlar kullanılmıştır. Sonuçlar, teorik korelasyonların sadece laminer ve türbülanslı bölgelerdeki HAD sonuçları ile oldukça tutarlı olduğunu ve ayrıca geçişin sadece HAD simülasyonları ile tahmin edilebileceğini göstermiştir. Öte yandan, bir Aktif Akış Kontrolü yöntemi olarak ısıtmanın, düz bir plaka üzerindeki geçiş rejimini geciktirmede faydalı olduğu bulunmuştur.
Anahtar Kelimeler: HAD, Zorlanmış Taşınım, Sınır Tabaka Akışı, Aktif Akış Kontrolü, Geçiş Bölgesinin Geciktirilmesi

I. INTRODUCTION

Flow control methods have been used for a long time with various targets including betterment of aerodynamic performances. Manipulation of transition region by heating and cooling is one of the commonly applied AFC strategies. Particularly, decreasing friction forces has been the subject of such work in literature by using active and passive flow control methods.

Flow control methods are divided into two groups as Active Flow Control (AFC) and Passive Flow Control (PFC). In PFC methods, geometric manipulation of the configuration is applied without using additional power; but in AFC methods an external energy input is required. The separating plate, a small control bar, surface roughness and grooved or protruding surfaces belong to PFC methods. Commonly encountered applications of AFC methods include blowing into or suction from the boundary layer, heating or cooling of the solid surface, delivery of micro bubbles or particles into the base flow, acoustic excitation, using rotating or oscillating objects and electromagnetic forces [1].

Flow control research dates back to the definition of the boundary layer by Ludwig Prandtl in 1904. According to

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the needs in military and civil aviation, flow control methods were extensively studied and applied especially to military aircrafts [2]. A comprehensive review about flow control was provided by Lachman (1961) [3] and more recently by Gad-el-Hak et al. (1998) [4]. Liepmann & Nosenchuck, (1982) used an AFC method to delay transition. T-S waves responsible for instability were introduced in a laminar boundary layer flow through periodic heating by flush-mounted heating elements. Experiments showed that nearly all the T-S waves could be eliminated by using a second downstream heating element with a suitable phase shift. A single element activated by measured shear stress in a feedback loop was used to reduce the amplitude of naturally occurring laminar instability waves. Thus, a significant increase in the Reynolds number in the transitional regime was achieved [5]. Dovgal et al. performed experimental studies in order to obtain transition delay by local heating and showed that local heating was capable of maintaining a laminar boundary layer [6]. Canbolat et al. investigated transition control over a flat plate numerically and concluded that a heated flat plate induced the decrease of the local skin friction coefficient in the turbulent region for an incompressible gaseous flow [7]. Subasi and Gunes performed numerical calculations to represent the effect of a heated plate on local skin friction coefficient and showed that heating delayed transition and decreased the skin friction coefficient in turbulent region [8]. The selection of the appropriate turbulence model in engineering problems involving external flows around UAV (Unmanned Air Vehicles) [9] and buildings [10] is vital to obtain consistent aerodynamic performance characteristics.

In the present study, CFD calculations have been performed to manipulate transition regime of the boundary layer under various constant surface temperatures which is a kind of AFC. The CFD results were found to be consistent only in the laminar and turbulent regimes with theoretical formulations for local skin friction and convective heat transfer coefficients, since there are no available theoretical formulations for them in transitional regime. It should be noted that theoretical correlations were used at a constant surface temperature with constant thermos-physical properties accordingly in the laminar and turbulent flow regions [11]. Besides, the effects of the surface temperature on transition delay were also presented.

II. METHODOLOGY

Finite-volume-based ANSYS-Fluent flow solver is used to perform CFD calculations in order to predict the flow and temperature domains and consequently the derived local skin friction and heat transfer coefficient along the flat plate. Computational domain, mesh and mesh convergence tests, imposed boundary conditions, governing equations are presented in this section.

2.1. Geometry, Mesh and Mesh Convergence Tests

In this study, computational domain is determined as 2-D domain as shown in Figure 1. In order to satisfy the condition for a fully developed turbulent boundary layer velocity profile, a distance of 0.15 m upstream of the plate is used which is defined by symmetry boundary condition.

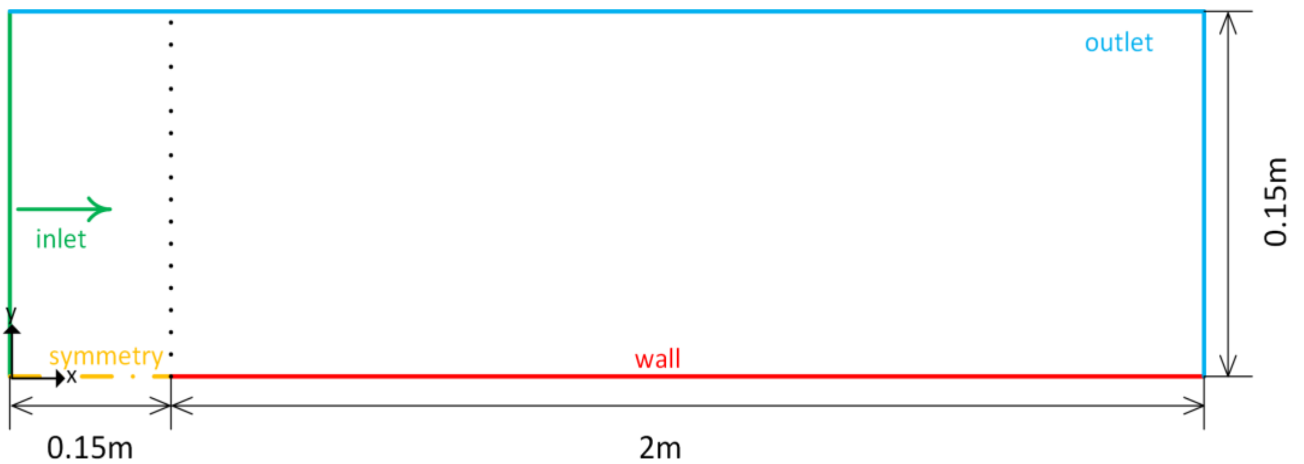


Figure 1. 2D geometry of the flow domain

The computational domain is generated with structured meshing. The whole domain is meshed with quad elements in both directions where the smallest cell in the boundary layer has a height of 0.75 mm. The details of the mesh in the vicinity of the wall can be seen in Figure 2. To predict the boundary layer development precisely, inflation method is applied to the wall boundary with 35 layers and 1.2 growth rate.

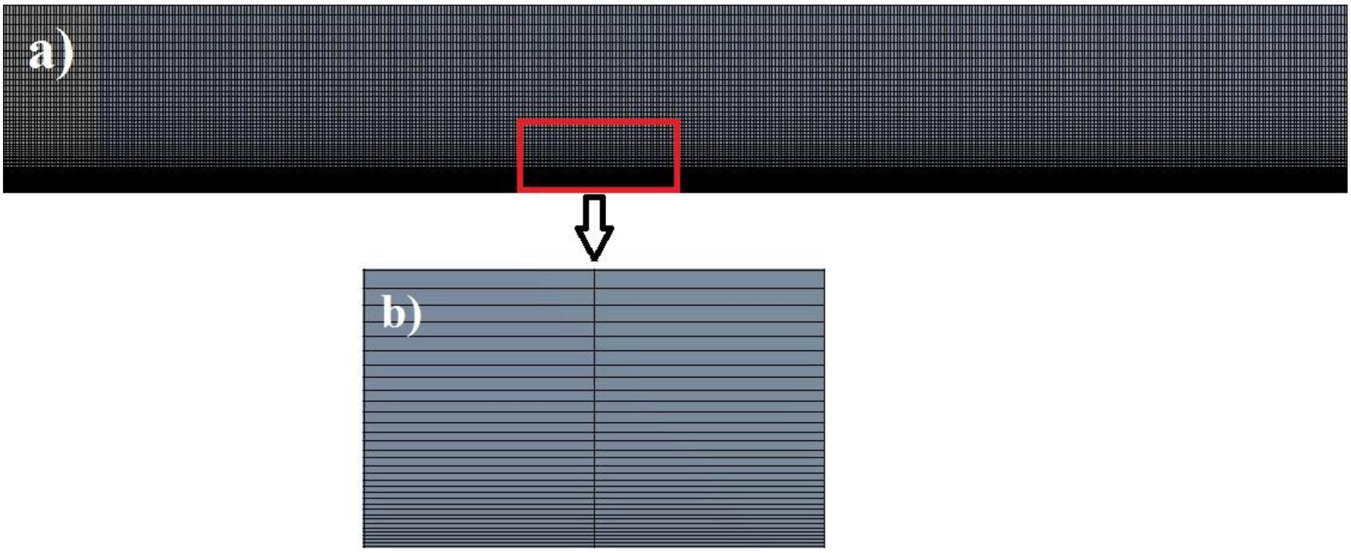


Figure 2. Two-dimensional mesh of fluid domain a) general view b) detailed view of boundary layer

An important criterion in the mesh dependency tests is the wall y^+ value according to the turbulence model. As mesh dependency tests in Figure 3 show nearly 590000 quad elements are found to be sufficient for further calculations. The wall y^+ values should be around 1 for Transition SST turbulence model and this is a necessity for accurate prediction of the boundary layer flow consistent with experiments [12].

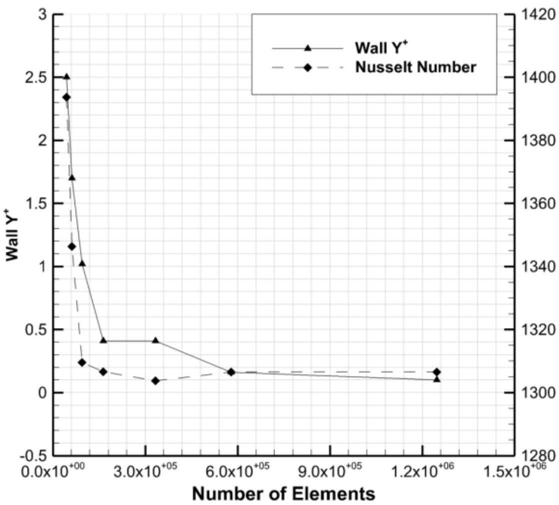


Figure 3. Mesh dependency tests

2.2. Governing Equations and Boundary Conditions

Conservation equations of mass, momentum (Navier-Stokes equations) and energy are given in Equations (1a), (1b) and (1c), respectively.

In the current study, steady and incompressible flow assumptions are done.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1a)$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \quad (1b)$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial}{\partial x_j}\left[u_i\left(\rho E + p\right)\right] = \frac{\partial}{\partial x_j}\left[\left(k + \frac{c_p \mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j} + u_i\left(\tau_i\right)_{eff}\right] + S_h \quad (1c)$$

In the Equation (1) ρ, u, μ, E, c_p, τ and S_h represent density, velocity, dynamic viscosity, internal energy, specific heat, shear stress and source term, respectively. The transition SST model is based on the coupling of the SST –k- ω transport equations with two other transport equations, one for the intermittency and one for the transition onset criteria, in terms of momentum-thickness Reynolds number. The details of the turbulence model can be found in [13].

Hydrodynamic and thermal inlet boundary conditions are constant free-stream velocity of 15 m/s with 3 % turbulence intensity and 27°C constant free-stream temperature. The plate surface is wall with no-slip boundary condition and has constant surface temperatures such as 50°C, 75°C, 100°C and 125°C. The outlet is defined with pressure outlet.

Boundary conditions are summarized in Table 1. backflow values in the boundary conditions for outlet applies if backflow occurs. Due to the nature of the problem backflow doesn't occur.

Table 1. Boundary conditions of the problem

Boundary name:	***Hydrodynamic Boundary Conditions:***	***Thermal Boundary Conditions:***
Inlet	u =15 m/s, v = 0 m/s, I = 3%	T = 27°C
Outlet	p=0 $I_{backflow}$ = 3%	$T_{backflow}$ = 27°C
Plate Surface	u =0 m/s, v = 0 m/s (no slip)	50°C, 75°C, 100°C and 125°C
Symmetry	$\frac{\partial u}{\partial y} = 0$	$\frac{\partial T}{\partial y} = 0$

It is assumed that the film temperature (T_f) is the average of the surface and free-stream temperatures [8] as shown in Equation 2.

$$T_f = \frac{T_s + T_\infty}{2} \tag{2}$$

As suggested in [11], the average film temperature is used to determine the constant thermo-physical properties of air in simulations and tabulated in Table 2.

Table 2. Thermo-physical properties of air

T_s [°C]	**T_f [°C]**	**ρ [kg/m³]**	**μ [kg/ms]**	**k [W/mK]**	**c_p [J/kg K]**
50	38.5	1.1348	1.9055x10^{-5}	0.026930	1.0068x10^3
75	51	1.0892	1.9653x10^{-5}	0.027873	1.0075x10^3
100	63.5	1.0502	2.0195x10^{-5}	0.028730	1.0083x10^3
125	76	1.0110	2.0772x10^{-5}	0.026943	1.0092x10^3

Equation (3) and Equation (4) show the local wall shear stress and friction coefficient for the laminar boundary layer flow over a flat plate, respectively. The local friction coefficients for the laminar and turbulent boundary layer zones can be theoretically predicted by Equation (5) and Equation (6), respectively [11].

$$\tau_{s,x} = 0.332 \times u_\infty \sqrt{\frac{\rho \mu u_\infty}{x}} \tag{3}$$

$$C_{f,x} = \frac{2\tau_{s,x}}{\rho u_\infty^{\,2}} \tag{4}$$

$$C_{f,x,lam} = 0.664\,\mathrm{Re}_x^{-1/2} \tag{5}$$

$$C_{f,x,\mathrm{tur}} = 0.027\,\mathrm{Re}_x^{-1/7} \tag{6}$$

In Equations (3)-(6), u_∞, Re_x and $C_{f,x}$ denote free-stream velocity, local Reynolds number, local skin friction coefficient, respectively. The mean skin friction coefficient along the flat plate can be calculated by Equation (7). In the equation, x_c represents the distance from the leading edge of the flat plate where transition initiates. These theoretical approaches are used to confirm the numerical results in the laminar and turbulent regimes of the boundary layer flow.

$$\bar{C}_{f,L} = \frac{1}{L}\left(\int_0^{x_c} C_{f,x,lam}\,dx + \int_{x_c}^{L} C_{f,x,\mathrm{turb}}\,dx \right) \tag{7}$$

$$\bar{C}_{f,L} = 0.074\,\mathrm{Re}_L^{-1/5} - \frac{2}{\mathrm{Re}_L}\left[0.037\,\mathrm{Re}_{x,c}^{\,4/5} - 0.664\,\mathrm{Re}_{x,c}^{\,1/2} \right] \tag{8}$$

Similar to the wall friction coefficient, local Nusselt number variation along the flat plate are calculated. The local Nusselt number in Equation (9) can be written for the laminar and turbulent regions as indicated in Equation (10) and Equation (11), respectively.

$$Nu_x = \frac{h_x x}{k} \tag{9}$$

$$Nu_{x,lam} = 0.332\,\mathrm{Re}_x^{1/2}\,\mathrm{Pr}^{1/3} \tag{10}$$

$$Nu_{x,tur} = 0.0296\,\mathrm{Re}_x^{4/5}\,\mathrm{Pr}^{1/3} \tag{11}$$

The theoretical approaches for the mean heat transfer coefficient in Equation (12) and Equation (13) in addition to mean Nusselt number in Equation (14) are utilized for the validation of CFD results. These equations can be found in [11].

$$\bar{h}_L = \frac{1}{L}\left(\int_0^{x_c} h_{lam}\,dx + \int_{x_c}^{L} h_{\mathrm{turb}}\,dx \right) \tag{12}$$

$$\bar{h}_L = \frac{k}{L}\,\mathrm{Pr}^{1/3} \, x \left[0.332 \left(\frac{u_\infty}{\upsilon} \right)^{1/2} \int_0^{x_c} \frac{dx}{x^{1/2}} + 0.0296 \left(\frac{u_\infty}{\upsilon} \right)^{4/5} \int_{x_c}^{L} \frac{dx}{x^{1/5}} \right] \tag{13}$$

$$\overline{Nu}_L = \mathrm{Pr}^{1/3} \, x \left[0.0037\,\mathrm{Re}^{4/5} - \left(0.037\,\mathrm{Re}_{x,c}^{\,4/5} - 0.664\,\mathrm{Re}_{x,c}^{\,1/2} \right) \right] \tag{14}$$

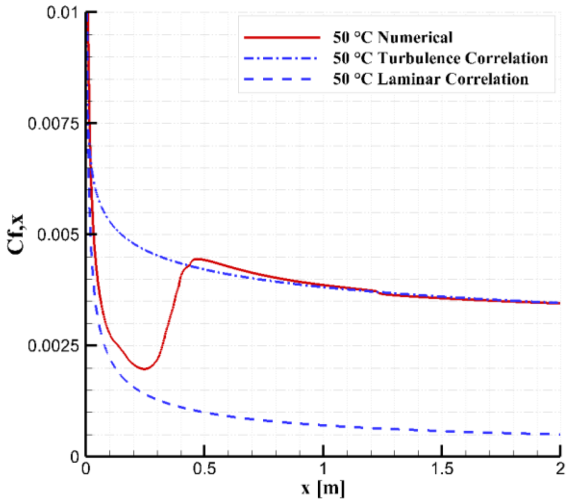
III. RESULTS

In this section, the numerically obtained local skin friction coefficients and local heat transfer coefficients are compared with theoretical correlations at various constant surface temperatures. It should be pointed out, that the theoretical correlations for the local skin friction coefficient and local heat transfer coefficient are only valid in the laminar and fully turbulent flow regions, since the only way to predict transitional change in the boundary layer is numerical simulation. Figure 4. shows the comparison of the local skin friction coefficients from theoretical and numerical calculations.

As it can be seen in Figure 4. and Figure 5, numerical results are highly compatible with theoretical correlations in the laminar and fully turbulent flow regions. It should be noted, that x_c in the theoretical formulations in Equation (7) and Equation (11) has been determined according to the critical Reynolds number 500.000.

Table 3. shows the numerical and theoretical average flow and heat transfer characteristics. With increasing surface temperature, the overall skin friction coefficient increases as well which is associated to the increasing dynamic viscosity and related friction forces on the flat plate at that certain temperature.

Temperature dependency of the dynamic viscosity also affects the Nusselt number which can be expressed in terms of the Re and Pr. In the current study, Pr is constant, hence Nu changes only with Re. In gaseous flows, with increasing temperature, dynamic viscosity increases and as a result both local Re and as well as the overall values for Nu tend to decrease.



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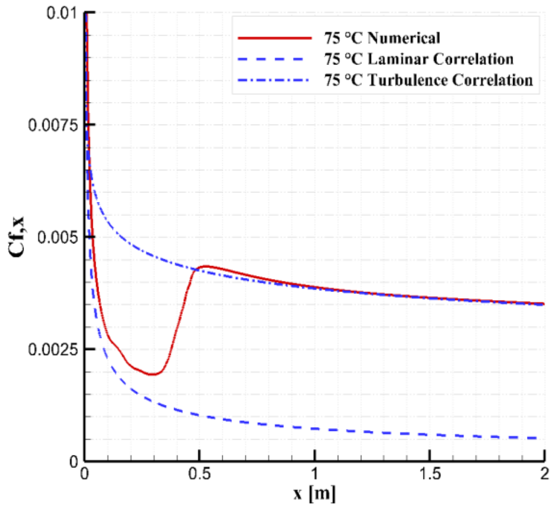

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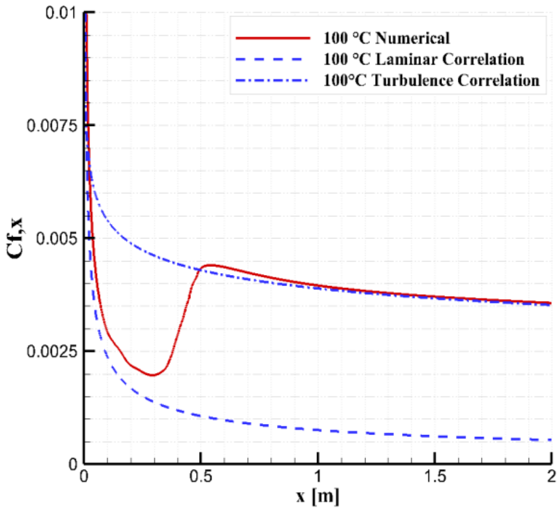

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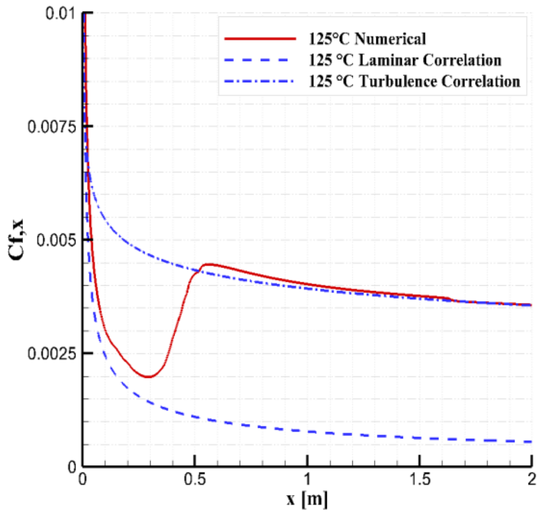
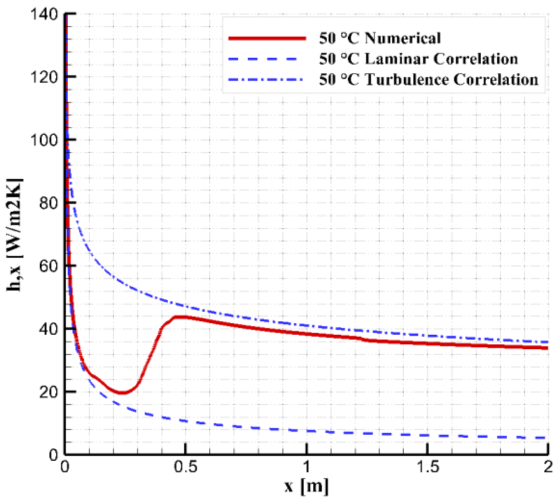


(d)

Figure 4. Variation of local skin friction coefficients in streamwise direction at different surface temperatures.

Table 3. Comparison of the average flow and heat transfer characteristics

T_s [°C]	$\overline{C}_{f,L}$ (CFD)	$\overline{C}_{f,L}$ (Theoretical)	Mean Relative Error (%)
50	0.00369	0.00330	10.8
75	0.00371	0.00331	10
100	0.00373	0.00332	11
125	0.00378	0.00334	11.6
T_s [°C]	**$\overline{h}_L$ (CFD)**	**$\overline{h}_L$ (Theoretical)**	**Mean Relative Error (%)**
50	36.30	35.78	1.4
75	34.71	34.18	1.5
100	34.02	33.22	2.3
125	33.18	32.26	2.8



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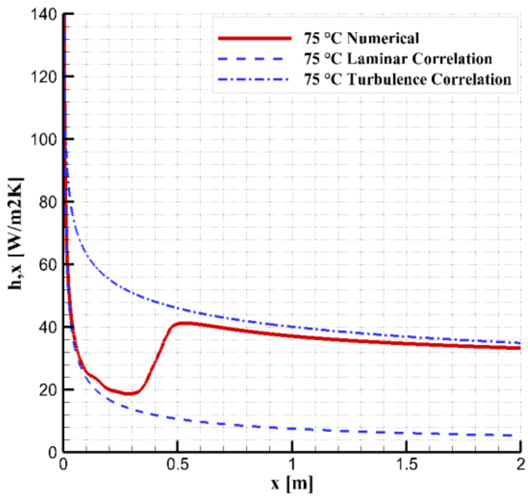

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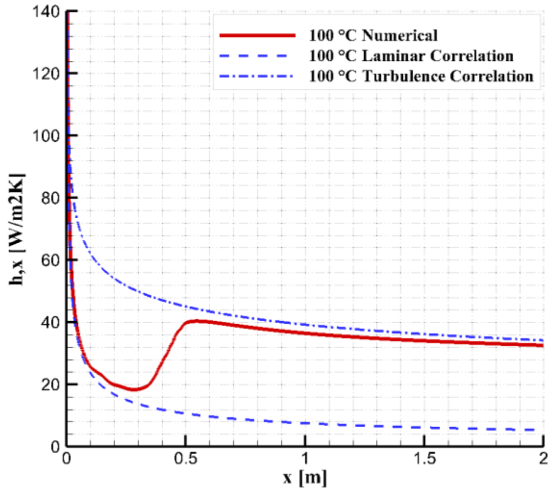

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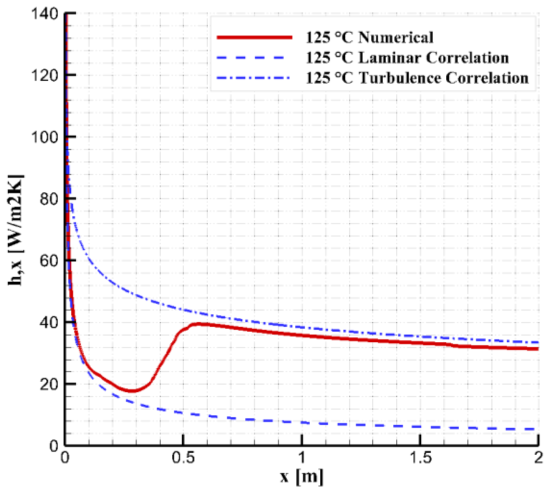

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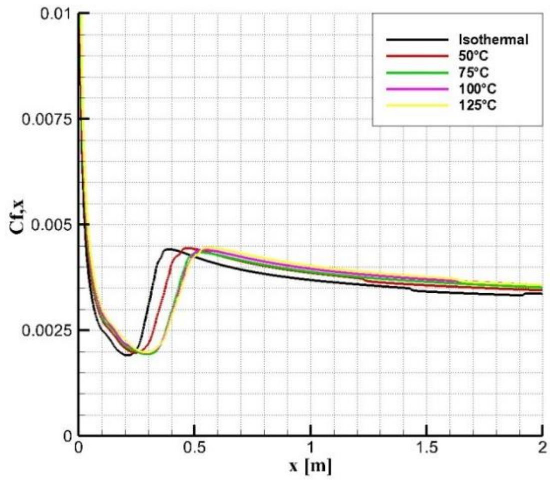
Figure 5. Variation of local heat transfer coefficients in streamwise direction at different surface temperatures.



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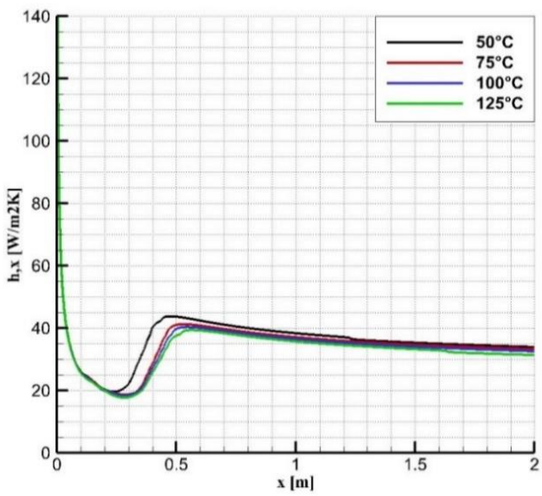

(b)

Figure 6. Local skin friction coefficient and local heat transfer coefficient variation for different surface temperatures.

Figure 6. demonstrates how the transition location of the boundary layer flow is influenced by active flow control if constant surface temperature is applied. Increasing the plate's surface temperature delays transition, since local Re decreases with increasing dynamic viscosity. In addition to that, local skin friction coefficients in the turbulent region increases which results in a higher overall skin friction coefficient at high temperatures. Transition delay also affects local heat transfer coefficients. Contrary to the local skin friction coefficient, local heat transfer coefficients tend to decrease in the turbulent region yielding lower overall heat transfer coefficients at high temperatures.

IV. CONCLUSION

In this study, flow and forced convection over a flat plate is investigated with ANSYS-Fluent and numerical results are verified by theoretical correlations in literature. It is shown that CFD is an important tool to predict transition behavior inside the boundary layer flow. In the laminar and fully turbulent regions, local skin friction and heat transfer coefficients are found to be in agreement with the correlations. It is shown that increasing surface temperature of the plate as an active flow control method is effective in transition delay. Finally, active flow control method causes an increased overall skin friction coefficient and decreased heat transfer coefficient in the turbulent region if high surface temperatures are applied.

NOMENCLATURE

C_f	Skin friction coefficient [-]
c_p	Specific heat [J/kgK]
E	Internal energy [J/kg]
h	Heat transfer coefficient [W/m^{2}K]
I	Turbulence Intensity [%]
k	Thermal conductivity [W/mK]
k	Turbulence kinetic energy [m^2/s^2]
L	Length of the plate [m]
Nu	Nusselt number [-]
Pr	Prandtl number [-]
Re	Reynolds number [-]
S_h	Heat source [W/m^3]
T	Temperature [°C]
t	Time [s]
u	x-velocity component [m/s]
v	y-velocity component [m/s]
x	Streamwise direction
y	Wall normal direction

Greeks

μ	Dynamic viscosity [kg/ms]
ν	Kinematic Viscosity [m^2/s]
ρ	Density [kg/m^3]
τ	Shear stress [Pa]
ω	Specific dissipation rate of turbulence [1/s]

Abbreviations:

CFD	Computational Fluid Dynamics
SST	Shear Stress Transport

Subscripts:

c	Critical
f	Film zone
lam	Laminar
tur	Turbulent
s	Surface
∞	Free stream

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