4.1 Applicability of the Methodology over Finite Flat Plate

In [3,4], it is proposed that the velocity used to estimate the convective time x/U_e along the flat plate should be U_e. However, a finite flat plate model with a rounded step is used for testing. This means that U_e is not constant everywhere along the model and its measurement would be rather difficult. It would be much more convenient to use the free-stream velocity U_∞, as it could be verifyied by CFD.

The free-stream conditions used for the analysis are in Table 1. Local thermodynamic equilibrium (LTE) is imposed at the freestream where the species concentrations are specified by VKI Mutation Library. Wall temperature is always set at 350 K. The results can be seen in Fig. 4. The heat flux curves converge along x/U_∞ for the same pressure. This means that the obtained boundary layers are equivalent and the methodology is applicable with the free-stream velocity U_∞. Pressure is affecting chemical reactions and as a consequence, it defines the resulting heat flux curves. This fact has an important consequence for testing considering that the easiest way to modify U_∞ in the Plasmatron is by changing static pressure P. Given the results in Fig. 4, U_∞ should be varied with the mass flow of gas injected at the torch.

Table 1 Free-stream conditions for CFD analysis

Case	U_∞, m/s	T_∞, K	P_∞, Pa
1	257.45	4800	1500
2	375.00	4800	1500
3	514.93	4800	1500
4	257.64	4800	3000
5	375.00	4800	3000
6	514.93	4800	3000

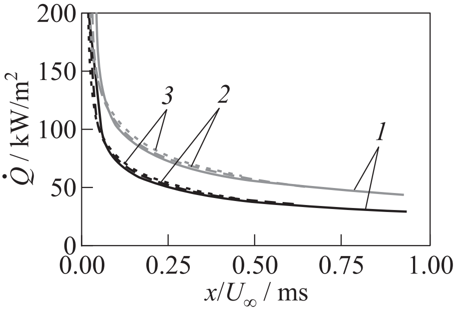

Figure 4 Off-stagnation point methodology applied with U_∞: *1* — 257 m/s; *2* — 375 m/s; *3* — 514 m/s; black curves refer to 15 mbar; and grey curves refer to 30 mbar

4.2 Reference Enthalpy and Velocity

It is reasonable to think that the fact of having a gradient in the free-stream properties could significantly influence chemical reactions in the bulk of the boundary layer. However, even if the simplifying assumption of a uniform free stream is rather convenient, it is difficult to achieve in real testing conditions with a plasma torch. Then, the study of the influence of a jet profile discharged on the flat plate becomes a necessity. To analyze this effect, both enthalpy and velocity

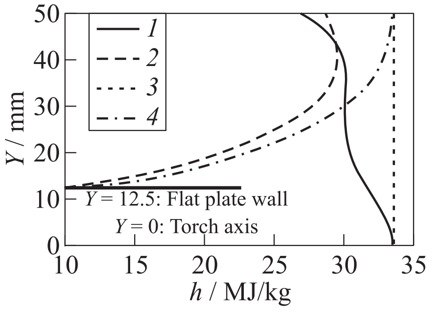

Figure 5 Uniform and jet enthalpy profiles comparison (evaluation at 20 cm from the leading edge): *1* — jet free stream; *2* — boundary layer from jet at 20 cm from the leading edge; *3* — uniform free stream; and *4* — boundary layer from uniform at 20 cm from the leading edge

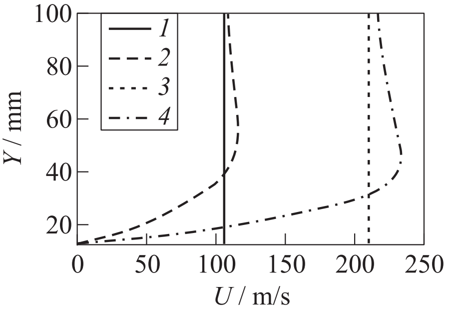

Figure 6 Effect of varying U_∞ on U_e (evaluation at 20 cm from the leading edge): *1* — $U_\infty = 105$ m/s; *2* — boudary layer for $U_\infty = 105$ m/s; *3* — $U_\infty = 210$ m/s; and *4* — boundary layer for $U_\infty = 210$ m/s

profiles are rebuilt from experimental measurements [9, 10] across the plasma torch. These profiles, together with species concentrations under equilibrium, have been introduced as input boundary conditions in the simulations. The results are shown in Fig. 5 where the enthalpy profile at 20 cm from the leading edge is compared to the one obtained under uniform conditions. Free-stream profiles are plotted too. It appears reasonable to define the outer edge as the point where enthalpy reaches its free-stream value. In the profile corresponding to the free-stream jet, the enthalpy at the outer edge is not the same as the one located at the axis of the plasma torch. Then, free-stream enthalpy on the axis should be considered as a reference and not as the one really present at the outer edge. Another conclusion from Fig. 5 is that enthalpy gradients are not significantly different between the two boundary layers. Hence, the assumption of uniform free-stream conditions during the tests should not be a limitation for the methodology. The same conclusions apply at different locations of the flat plate.

In addition, the assurance that a variation in U_∞ leads to the same variation at the outer edge U_e is required. This has also been verified and it is shown in Fig. 6. Under the same h_∞ and P conditions, if U_∞ is varied from 210 to 105 m/s, U_e is also halved at 20 cm from the leading edge of the flat plate model. The same result is checked at different x-coordinates over the model.

5 TESTING CAMPAIGN

The off-stagnation point methodology has been applied at the VKI-Plasmatron facility. The experimental setup is shown in Fig. 7. A copper calorimeter (called

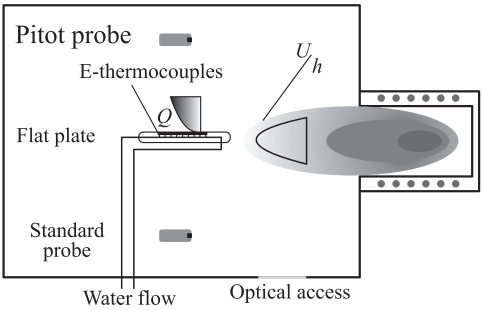

Figure 7 Schematics of VKI-Plasmatron configuration for off-stagnation point testing

Standard Probe at VKI) and a Pitot probe are injected first into the plasma torch to define the testing conditions of heat flux and pressure at stagnation point, respectively. They are used to rebuild the free-stream conditions U_∞ and h_∞ together with the in-house boundary layer code [11] and ICP simulations [12]. Then, the flat plate model is introduced into the plasma jet and the temperature coming from the themocouoples is stored using the data acquisition system.

The Plasmatron test chamber is equipped with an absolute pressure transducer Memberanovac DM12, Leybold Vacuum, OC Oerlikon Corporation AG, Pfäffikon, Switzerland able to measure static pressure with ± 2% of uncertainty. For the Pitot line, a variable reluctance pressure transducer Validyne DP-15 Validyne Engineering Corp., Northridge, CA, USA is used. Its output is amplified and corrected through a voltage demodulator CD-15 Valydine Engineering Corp., Northridge, CA, USA. Both pressure transducer and demodulator are calibrated by means of a Betz water manometer and their uncertainty is ± 10% due to plasma torch fluctuations. The thermocouples used in the flat plate calorimenter are type-E with an uncertainty of ± 0.2 K.

5.1 Off-Stagnation Point Results

The testing procedure described above is repeated for 16 and 8 g/s of air-plasma for several values of stagnation point heat flux and at constant pressure ($P = 1500$ Pa). The off-stagnation heat flux distributions with the same static enthalpy are selected. The change of the gas mass flow leads to a variation in the free-stream velocity U_∞. The testing conditions considered are presented in Table 2. The off-stagnation point methodology is applied and the results are shown in Fig. 8. Since the difference in h_∞ is only 1%, it is reasonable to assume that chemical composition of the plasma is kept constant between the two cases. The difference in U_∞ leads to the conclusion that a 32 percent boundary layer reduction is achieved when passing from 16 to 8 g/s air flow.

Table 2 Testing conditions considered for off-stagnation point methodology application

$\dot{m}$, g/s	h_e, MJ/kg	U_∞, m/s	P, Pa
16	11.73	839.93	1500
8	11.61	572.21	1500

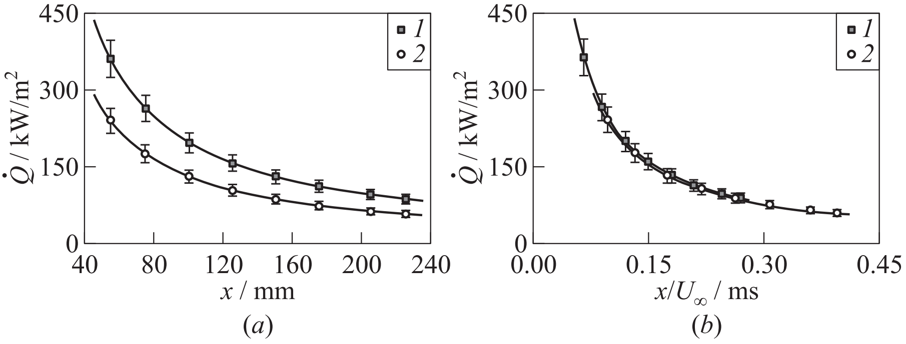

Figure 8 Off-stagnation point methodology applied at VKI-Plasmatron facility: (*a*) $\dot{Q}$ over x and (*b*) $\dot{Q}$ over x/U_∞: *1* — 16 g/s: h_∞ = 11.73 MJ/kg and U_∞ = 839.93 m/s; and *2* — 8 g/s: h_∞ = 11.61 MJ/kg and U_∞ = 572.21 m/s

Uncertainty analysis studies can be found in [6] for the stagnation point heat flux Standard Probe. Same levels of uncertainty are expected at the flat plate calorimeter since both are based on the same measurement principles. Heat flux accuracy is assumed to be ±10% following

$$\frac{\delta\dot{Q}}{\dot{Q}} = \sqrt{\left(\frac{\delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\delta c_p}{c_p}\right)^2 + \left(\frac{\delta(T_{\mathrm{out}} - T_{\mathrm{in}})}{T_{\mathrm{out}} - T_{\mathrm{in}}}\right)^2 + \left(\frac{\delta A}{A}\right)^2}$$

where ‘in’ and ‘out’ refer to input and output conditions at the sensor and A is the corresponding sensing area. Static pressure P and dynamic pressure P_{dyn} accuracies are ±10% and ±20%, respectively: the former due to fluctuactions of the vacuum pumps and the latter due to plasma torch instability. Propagation error through the rebuilding boundary layer code leads to ±10 percent uncertainty on h_∞.

6 CONCLUDING REMARKS

An off-stagnation point methodology that overcomes the model size limitation for high enthalpy facilities has been assessed. After a 2D CFD analysis, it is suggested that VKI-Plasmatron is suitable to apply this methodology. Care should be taken when changing the U_∞ since h_∞ and P determine chemical reactions in the bulk of the boundary layer. It is shown that applying the methodology with U_∞ instead of U_e remains acceptable as well as the assumption of uniform free-stream conditions. Finally, the methodology is successfully applied for the Plasmatron testing conditions considered in Table 2 obtaining a 32 percent reduced scale boundary layer over the flat plate model.

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