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INVESTIGATING RANS PREDICTIONS FOR HEAT AND MASS TRANSFER IN TURBULENT FLOW ACROSS A BACKWARD-FACING STEP

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1. ABSTRACT

As part of a flow accelerated corrosion investigation, the reliability of 4 RANS models, namely a 2-layer k-ε, the k-ω SST, the Elliptic Blending k-ε and the Elliptic Blending Reynolds Stress Model, for mass and heat transfer predictions (Sherwood and Nusselt numbers) is evaluated by reference to a recent experiment (Re_H=16-24,000, *Pr* = 0.707, *Sc* = 2.28). The C_f and velocity profiles, missing in the mass transfer study, are compared with data from DNS and experimental studies at higher and lower *Re* values. The study provides some confidence in qualitative predictions of heat/mass transfer with the Elliptic Blending RANS models.

2. INTRODUCTION

This Sherwood number RANS-predictions validation attempt is part of a larger parametric experimental rig optimisation RANS project [1] for flow accelerated corrosion (FAC) study in either water or liquid metal cooled nuclear power plants, but for which detailed flow data is very scarce. A valuable Backward Facing Step (BFS) experiment by Mittal et al. [2] provides Sherwood and Nusselt measurements. Since the mathematical laws of convection and diffusion of mass and thermal energy are identical when boundary conditions are analogous and thermal energy is considered as a passive scalar, they observed that correlations in the literature that use different exponents on *Re*, *Pr* or *Sc* are inconsistent, and instead suggested:

$$Nu_{max} \ or \ Sh_{max} = 0.142 \cdot Re_H^{0.65} \cdot (Pr \ or \ Sc)^{0.315} \quad (1)$$

Where *Pr* is the molecular Prandtl number and *Sc* is the Schmidt number. Measured heat and mass transfer of [2] at Re_H =16,200 & 24,400 for air (*Pr* = 0.707) and naphthalene sublimation (*Sc* = 2.28) coincide neatly after nondimensionalisation by (1). Since [3] only measured the upstream boundary layer (BL) velocity profiles, our CFD results are further compared to the velocity, C_p and C_f profiles of the Driver & Seegmiller [3] experiment: BL Re_θ =5,000 and BFS Re_H =36,000 and the DNS of Le et al. [4]: $Re_\theta = 667$, Re_H=5,100.

3. METHDOLOGY

In the 4 RANS model simulations presented here, the inlet conditions have been carefully tuned so that the upstream BL matches the experimental profile of Mittal et al. (2017) [2]. The velocity and turbulence profiles at the simulation domain inlet have been determined from preliminary computations of developing boundary layer flow, used to generate profiles that matched those at x = 12.7 mm upstream of the step. This tuning involved

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running a precursor flat plate 2D RANS simulation from which the BFS simulation's inlet profiles were extracted. Boundary layers are well developed in both experiment and simulations, as will be shown later, where all profiles collapse to the classic linear–log laws, plotted in wall friction coordinates using the wall shear stress (WSS). Down to the wall mesh refinement checks have been conducted.

4. RESULTS

In Figures 1 and 2, the experiment's *Sh* numbers at the two *Re* numbers are more consistent, whereas the *Nu* profiles are noisier. This illustrates that easier naphthalene concentration measurements are sometimes preferred to direct heat transfer measurements but proper *Pr/Sc* rescaling needs to be considered. The Reynolds Stress Elliptic Blending (EB) model matches somewhat the maximum *Sh* while the EB k-ε better predicts the Nu overall profile. The Standard two-layer k-ε and the k-ω SST models severely underpredict both heat and mass transfer coefficients.

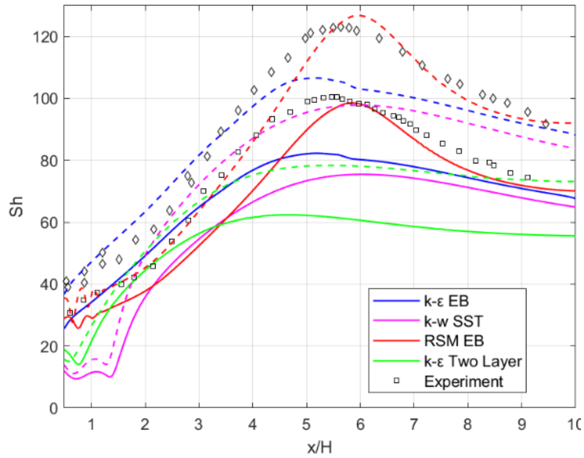

Figure 1: Naphthalene Sh at $U_\infty \approx 12.5m/s$ (solid line for model, square for Expt.) and $U_\infty \approx 17.5m/s$ (dashed line – models, diamond -Expt.)

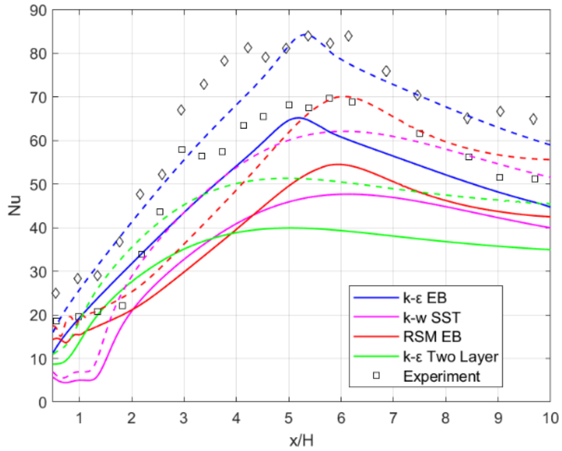

Figure 2: Air Nu at $U_\infty \approx 12.5m/s$ (solid line – model, square – Expt.) and $U_\infty \approx 17.5m/s$ (dashed line – models and diamond – Expt.)

Table 1: Maximum heat and mass transfer coefficients values and locations

Method	U_∞	$X_r\ (x/H)$	X_{max}, Sh	Sh_{max}	%	X_{max}, Nu	Nu_{max}	%
k-ε EB	12.50	5.77	5.16	82.26	-15.73	5.21	65.22	-3.66
RSM EB		5.8	5.83	98.54	0.95	5.94	54.54	-19.44
k-ε 2 Layer		5.55	4.64	62.36	-36.11	5.05	39.95	-40.99
k-ω SST		6.56	6.05	75.49	-22.66	6.14	47.7	-29.54
Experiment	12.53	*	5.58	97.61	-	5.48	67.7	-
k-ε EB	17.50	5.85	5.16	106.61	-13.27	5.35	84.35	0.45
RSM EB		6.09	5.97	126.78	3.13	6.04	70.13	-16.48
k-ε 2 Layer		5.56	5.46	78.33	-36.28	4.97	62.39	-25.7
k-ω SST		6.67	5.96	97.83	-20.42	6.05	62.83	-25.17
Experiment	17.47	*	5.76	122.93	-	5.17	83.97	-

The maximum levels of the dimensionless heat and mass transfer coefficients, Nu_{max} and Sh_{max} , and their locations X_{max}, are reported in Table 1. The reattachment position X_r was not measured in Mittal et al. but their estimations from their literature review place the locations of X_r after that of X_{max}. They observed that the intuitive X_r and X_{max} coincidence is rarely true. The dimensionless *Nu* and *Sh* numbers quantify the increased wall-to-fluid transfers, compared to pure diffusion of either heat or mass in a static fluid layer, due to:

a) Pure streamwise convection, as present in laminar pipe flows where $Nu \sim Re^{1/2}$;
b) Wall-normal diffusion enhanced by turbulence, with increased $Nu \sim Re^{4/5}$;

c) Jet impinging perpendicularly on heated plate inducing a very sharp *Nu* peak under the axis of the jet and due only to wall normal convection of cold fluid;
d) Free shear-layer sweeping of the wall, as the secondary peak found under a turbulent jet but away from the axis;
e) Coherent structures, as in a Von-Karman vortex street in the wake of a cylinder inserted in a BL, known to be present in BFS flows but not discussed here.

5. CONCLUSIONS

Four RANS models were used to study the turbulent mass/heat transfer in the BFS flow. The empirical mass transfer data produced by Mittal et al. [2] were used for validation. To the best of our knowledge, no one has reported the RANS simulation of this case. Furthermore, the reference experiment was the first to apply the same boundary conditions of uniform wall temperature and concentration in the recirculation and reattachment areas [2]. The recirculation region was analysed, here, via the velocity streamlines, C_f plots and the Nu and Sh profiles.

The following conclusions were drawn:

- The RSM EB and k-ε EB predicted fairly well the main recirculation bubble but somewhat underestimated the secondary one. The RSM EB yielded a better estimation of the local Sh_{max}, while the k-ε EB shows a better estimation of the overall trend of the *Nu* profile. The k-ω SST showed an excessive extent of the main and secondary bubbles, severely underestimating *Nu* and *Sh* throughout.
- The assumption of [2] that the maximum *Sh/Nu* location is upstream of the reattachment location (i.e. X_{mas}<X_r) was investigated and attributed to the lower angle of the streamlines near reattachment as observed with the EVM. The shift is absent when streamlines reattach nearly perpendicularly to the wall as with the RSM (impinging jet effect), or with the EB EVM at a higher Re.
- Demonstration of the $m = 0.65$ scaling by (1) suggested by [2], which falls between the $m =$ 0.5 and 0.8 values in the laminar boundary layer Nu correlation and the Dittus Boelter correlation, revealed that the models' profiles require a higher m value to overlap.
- It is recommended to run multiple RANS models to test the sensitivity of the case to model parameters, thereby increasing confidence in the results.

Finally, the present study gives some confidence in qualitative predictions of mass transfer with "Elliptic Blending" down-to-the-wall RANS models. CFD can thus be used to better understand the typical corrosion-erosion experimental setups. Furthermore, the analogy between heat and mass transfer can aid in linking corrosion-erosion observations with dimensionless factors (e.g. *Sh* and *Nu*). This could fill a knowledge gap in the experimental systems built to study corrosion-erosion.

REFERENCES

[1] A. E. A. Ali, A. Cioncolini, D. Laurence, and H. Iacovides, "Liquid lead flow-accelerated corrosion testing with the rotating cage set-up: A CFD optimisation," *Annals of Nuclear Energy,* vol. 165, p. 108620, 2022/01/01/ 2022, doi: https://doi.org/10.1016/j.anucene.2021.108620.
[2] R. Mittal, U. Madanan, and R. J. Goldstein, "The heat/mass transfer analogy for a backward facing step," *International Journal of Heat and Mass Transfer,* vol. 113, pp. 411-422, 2017, doi: 10.1016/j.ijheatmasstransfer.2017.05.087.
[3] D. M. Driver and H. L. Seegmiller, "Features of a reattaching turbulent shear layer in divergent channelflow," *AIAA journal,* vol. 23, no. 2, pp. 163-171, 1985.
[4] H. Le, P. Moin, and J. Kim, "Direct numerical simulation of turbulent flow over a backward-facing step," *Journal of Fluid Mechanics,* vol. 330, pp. 349-374, 1997, doi: 10.1017/S0022112096003941.