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Setting-up of reference solutions and characterization of URANS models for turbulent forced convection around a heated square cylinder

Xavier NICOLAS¹, Hua SUN¹, Yannick SOMMERER²

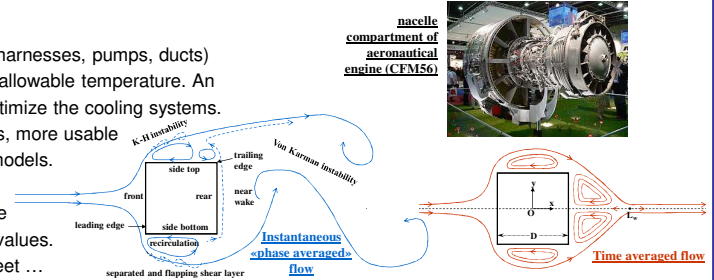
¹ Université Paris Est, MSME UMR 8208 CNRS, 5 Bd Descartes, 77454 Marne la Vallée Cedex 2, France
² Airbus, 316 Route de Bayonne, 31060 Toulouse Cedex 09, France

TI 2018

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Introduction

- CONTEXT:** in the nacelle compartment of aeronautical engines, the equipment (valves, electrical harnesses, pumps, ducts) is submitted to large heat fluxes; so it must sometimes be air-cooled to never exceed a maximum allowable temperature. An accurate prediction of the local convective heat transfer, h , or Nusselt number, Nu , is crucial to optimize the cooling systems.
- AIM:** to define if the prediction of h around heated bluff bodies is possible from URANS simulations, more usable than LES in an industrial context. Different $k-\epsilon$ and $k-\omega$ models are tested with different near wall models.
- METHODOLOGY:** comparisons with the experiments by Lyn and Rodi [JFM, 1994, 1995] of a flow at $Re=U_\infty D/v=22,000$ around a non heated square cylinder (ERCOFAC benchmark), and use of Igarashi [IJHMT, 1986] and Yoo et al. [JHT, 2003] experiments for heated cylinders at other Re values.
- INTEREST:** configuration with detached boundary layers, Kelvin-Helmholtz instabilities, vortex street ...



URANS & near-wall models

$$\frac{\partial \langle u_i \rangle}{\partial x_i} = 0 \quad R_{ij} = -\rho \langle u_i' u_j' \rangle = 2\mu_t D_{ij} - \frac{2}{3} \rho k \delta_{ij} = \mu_t \left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij}$$

$$\rho \left(\frac{\partial \langle u_i \rangle}{\partial t} + \langle u_j \rangle \frac{\partial \langle u_i \rangle}{\partial x_j} \right) = -\frac{\partial \langle p \rangle}{\partial x_i} + \frac{\partial}{\partial x_j} [2\mu_t D_{ij} + R_{ij}]$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial [\langle u_i \rangle (\rho E + \langle p \rangle)]}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\lambda_{eff} \frac{\partial \langle T \rangle}{\partial x_j} + \langle u_i \rangle \tau_{ij,eff} \right] \quad \lambda_{eff} = \lambda + \frac{C_p \mu_t}{Pr_t}$$

$$k = \frac{\langle u_i' u_i' \rangle}{2} \quad u_i'(M, t) = \overline{u_i'(M)} + \overline{u_i'(M, t)} + u_i''(M, t) = \langle u_i' \rangle(M, t) + u_i''(M, t)$$

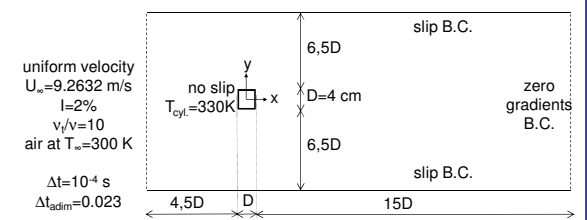
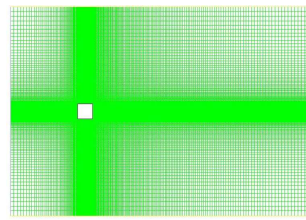
$$v_t = C_\mu \frac{k^2}{\epsilon} \quad \text{or} \quad v_t = \frac{k}{\omega}$$

+ transport eqs. for k and ϵ (or k and ω)

- k-ε standard:** only valid for fully-developed turbulent flows at large Re .
- k-ε RNG:** additional terms in the transport equations for k and ϵ to increase ϵ and reduce k and v_t in the highly strained flow regions.
- k-ε realizable:** satisfies mathematical constraints on the Reynolds stresses R_{ij} , (positivity, Schwarzq ineq.) consistent with turbulent flows physics.
- k-ω standard:** thanks to the specific dissipation rate ω , turbulence length scale well predicted close to the wall (low Re zone) but strong sensitivity to freestream conditions.
- k-ω SST:** blend, with a blending function, the robust and accurate formulation of the ω eq. in the near-wall region with the freestream independence of the ϵ eq. in the far field.
- Wall treatment for ε-eq.:** combine the Wolfstein two-layer model (for $y^+ \approx 1$) with y^+ insensitive wall function blending the linear and logarithmic (turbulent) law-of-the-wall.
- Wall treatment for ω-eq.:** y^+ -insensitive wall treatment by blending the viscous sublayer and logarithmic layer formulations (no need for a two-layer approach).

Numerical methods

- 2D incompressible URANS equations solved with ANSYS/Fluent;
- 2nd order time implicit scheme and 2nd order Quick scheme in space;
- velocity/pressure uncoupling: SIMPLEC or PISO;
- 7 cartesian grids used, from coarse (20×20 cells around the square cyl.; 10< y^+ <50) to fine (140×140 cells around the square cyl.; 0< y^+ <5);
- Time integration during 50 periods τ of the Von Karman vortices.

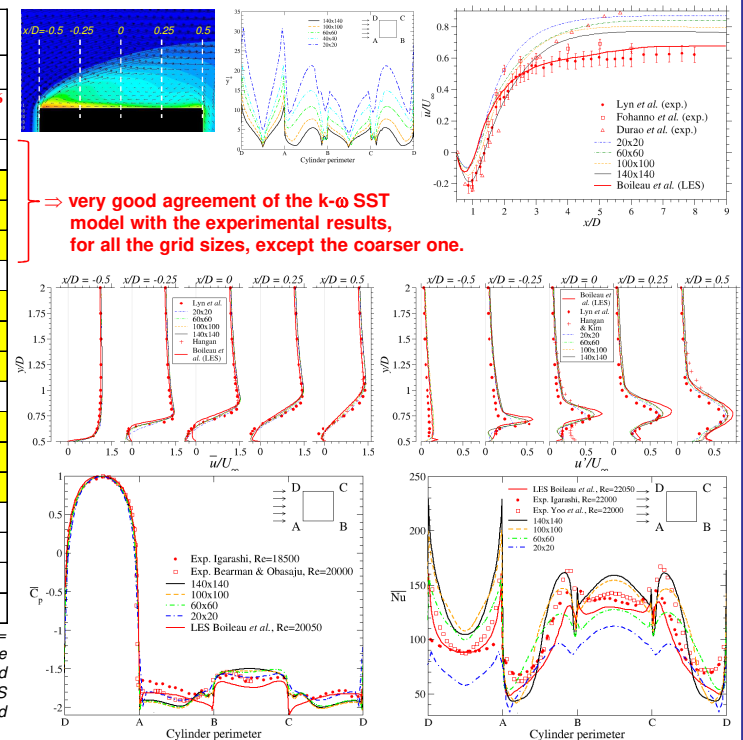


Results for 4 URANS models

Reference solutions	$N_x \times N_y$ mesh size (around square cyl)	L_w/D	S_t	$\overline{C_d}$	C_d'	C_l'	$\overline{C_p}$ [blockage correct*]	Nu_f front	Nu_s top/bot	Nu_r rear	Nu_t total
Exp. and LES synthesis by Sohankar (2006) : $Re=(5-5000) \times 10^3$			0.13±0.01	2.15±0.15	0.18±0.05	1.3±0.3					
Synthesis of 25 experim.: $I=0-2\%$		1.4±0.1	0.13±0.008	2.1±0.1	0.20±0.03	1.2±0.2	1.5 (1.4)±0.1	100±10	101±6	137±5	108±6
$Re=(10-200) \times 10^3$		1.4±0.1	0.13±0.008	1.9±0.1	0.20±0.03	1.1±0.2	1.3 (1.2)±0.1				
$I=10-14\%$		1.4±0.1	0.13±0.008	1.6±0.1	0.20±0.03	0.65±0.25	0.9 (0.8)±0.2				
k-ω SST $Re=22,000$ $I=2\%$	188×110 (20×20)	1.12	0.138	2.240 ±0.005	0.207 ±0.001	1.42 ±0.02	1.163	70.8	72.4 72.2	105.0	80.1 ±3.0
	290×190 (60×60)	1.13	0.132	2.215 ±0.005	0.239 ±0.005	1.47 ±0.01	1.192	120.1	95.3 95.5	120.8	108.0 ±3.8
	365×250 (100×100)	1.26	0.132	2.220 ±0.005	0.280 ±0.01	1.54 ±0.02	1.189	136.5	98.5 98.2	143.5	119.2 ±6
	435×310 (140×140)	1.325	0.122	2.220 ±0.005	0.325 ±0.01	1.57 ±0.02	1.197	135.9	96.7 97.0	148.0	119.4 ±7.6
k-ω SST low Re $Re=22,000$ $I=2\%$	188×110 (20×20)	1.24	0.138	2.225 ±0.005	0.234 ±0.001	1.337 ±0.005	1.143	70.9	69.7 69.5	105.2	78.9 ±3.9
	290×190 (60×60)	1.39	0.139	2.220 ±0.001	0.287 ±0.001	1.405 ±0.01	1.159	119.1	84.3 84.5	118.6	101.7 ±4.9
	365×250 (100×100)	1.52	0.129	2.25 ±0.01	0.37 ±0.02	1.45 ±0.02	1.170	132.6	85.9 85.9	138.4	110.7 ±7.3
	435×310 (140×140)	1.54	0.142	2.39 ±0.01	0.59 ±0.01	1.69 ±0.01	1.222	130.3	88.9 89.0	151.5	114.9 ±7.3
k-ε RNG $Re=22,000$ $I=2\%$	188×110 (20×20)	2.15	0.134	2.190 ±0.001	0.0081	0.567 ±0.001	0.839	119.8	87.8 87.9	85.5	95.2 ±0.2
	290×190 (60×60)	1.64	0.132	2.041 ±0.001	0.0277	1.048 ±0.01	0.972	125.9	88.0 88.0	91.1	98.2 ±0.3
	365×250 (100×100)	1.58	0.128	2.050 ±0.001	0.0328	1.048 ±0.02	0.993	141.6	90.7 90.6	95.1	104.5 ±0.8
	435×310 (140×140)	1.69	0.063	2.040 ±0.001	0.0291	0.956 ±0.001	0.983	143.3	91.2 91.2	93.6	104.8 ±0.8
k-ε realizable $Re=22,000$ $I=2\%$	188×110 (20×20)	1.98	0.147	1.949 ±0.001	0.0180	±0.634 ±0.0001	0.926	83.8	71.2 71.2	85.3	77.9 ±0.25
	290×190 (60×60)	1.38	0.135	2.190 ±0.001	0.0377	±1.333 ±0.001	1.146	121.6	75.2 75.3	89.9	90.5 ±0.9
	365×250 (100×100)	1.38	0.135	2.190 ±0.001	0.0377	±1.333 ±0.001	1.146	134.3	77.4 77.5	90.1	94.8 ±0.8
	435×310 (140×140)	1.33	0.126	2.210 ±0.001	0.0560	±1.538 ±0.001	1.182	133.1	79.4 79.4	84.1	94.0 ±0.8

Table: Global characteristics of the flow and heat transfer: L_w/D = dimensionless length of the wake; $S_t = fD/U_\infty$ = Strouhal number with f the frequency of the vortex shedding; $\overline{C_d}$, C_d' and C_l' = time averaged and RMS of the drag and lift coefficients; $\overline{C_p} = 2(p - p_\infty)/(\rho U_\infty^2)$ = time averaged base pressure coefficient, with \overline{p} the time averaged pressure on the rear face of the square cylinder; Nu = averaged Nusselt number. Comparison of the URANS results with reference solutions (in red) built from several experimental data of the literature. The values in bold are in the experimental ranges and the values in the yellow boxes are in a 10% accuracy from the references.

Results for k-ω SST model



→ very good agreement of the k-ω SST model with the experimental results, for all the grid sizes, except the coarser one.

- ## Conclusions :
- Setting-up of reference solutions for the present test case, from a synthesis of around 25 experimental results of the literature;
 - The **k-ω SST** model provides accurate results for the present test case, both for the flow dynamics and heat transfer, whatever the grid sizes for $y^+ < 20$;
 - These results are as accurate as the LES results by Boileau et al. (2013), but for a much smaller computational cost, compatible with industrial applications;
 - The Strouhal number, the averaged drag coefficient and the RMS of the lift coefficient are not enough selective criteria to qualify a numerical model;
 - The **k-ε** type models provide unsatisfactory results for the present test case, particularly for heat transfer. The low Reynolds version of the **k-ω SST** model does not improve it.

CPU time LES ~ O(100)
 CPU time URANS ~ O(1)