Tuning of Generalized K-Omega Turbulence Model for Prediction of Heat transfer and Pressure Drop for Helium Cooled Demo FW Channels

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Introduction

- The HCPB blanket concept for EU-DEMO fusion reactors employs **high-pressure (8 MPa) helium gas** as coolant for the plasma facing first wall. Up-to-date estimations for the total maximum of **heat flux go up to 0.73 MW/m²**. **60°-V-shaped rectangular ribs** show high heat transfer and are thus the subject of the presented studies.
- **Challenges in Turbulence Modelling**: LES provides high-fidelity results but is computationally expensive, RANS models are efficient, but struggle to predict complex flow features and underestimate the heat transfer up to 22 % .

Long Term Objectives

- Long term objectives of the qualification work for numerical simulations for the helium cooled First Wall channels of DEMO are to provide a consistent, fully validated and practically feasible (in terms of computing resources) **numerical approach** to provide simulations of **complete rib enhanced FW channels/ full-size blanket components.**

Approach: Generalized k-omega (GEKO) Model

- The **generalized k-omega (GEKO) turbulence model** offers higher accuracy predicting **heat transfer and pressure drop** compared to other RANS and Reynolds Stress Models (RSM).
- High-fidelity **Large Eddy Simulations (LES) as target data** are used to **optimize GEKO parameters** in Ansys Fluent.

Model Equations for Turbulent Kinetic Energy k and Dissipation ω:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P_k - C_\mu \rho k \omega + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \qquad P_k = -\tau_{ij}\frac{\partial u_i}{\partial x_j}$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = C_{\omega 1} F_1 \frac{\omega}{k} P_k + C_{\omega 2} F_2 \rho \omega^2 + \rho F_3 CD + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]$$

$$CD = \frac{2}{\sigma_\omega}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \qquad P_k = -\tau_{ij}\frac{\partial u_i}{\partial x_j}$$

$$\tau_{ij} = \tau_{ij}^{EV} - C_{CORNER}\frac{1.2\,\mu_t}{\max(0.3\omega, \sqrt{0.5(S_2 + \Omega_2)})}(S_{ik}\Omega_{kj} - \Omega_{ik}S_{kj})$$

Free coefficients

C_{sep}: reduces eddy-viscosity of entire flow field > increase flow separation

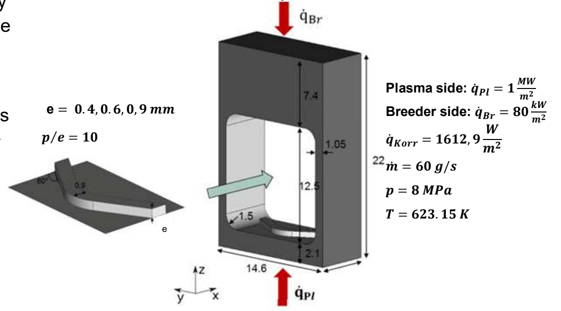
C_{nw}: affects only inner part of wall boundary layers, >increases wall shear stress

C_{CORNER}: Non-linear stress-strain term to account for secondary flows

C_{mix}: increase spreading rates of free shear flows

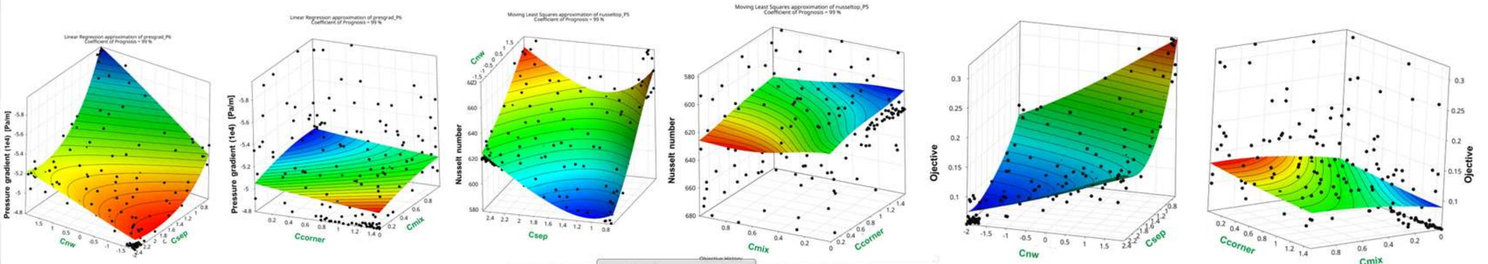
embedded in F_1, F_2, F_3

Target Data: Time averaged velocity and temperature fields of LES for FW test section with periodic heat transfer conditions



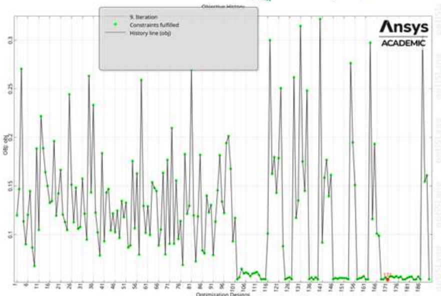
Focus on main parameters: Nusselt number **Nu** plasma side wall and pressure gradient **Pgrad** > Minimize for both difference between results for GEKO and LES

$$\text{Objective} = \sqrt{\left(\left(\frac{Nu_{Geko}}{Nu_{LES}}\right) - 1\right)^2 + \left(\left(\frac{Pgrad_{Geko}}{Pgrad_{LES}}\right) + 1\right)^2}$$

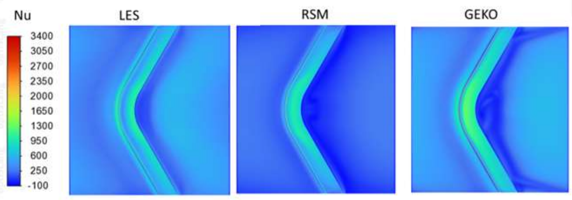


Ansys Ansys optiSLang:

- Input parameter: GEKO parameters C_{sep}, C_{nw}, C_{CORNER}, C_{CORNER}
- Output parameter: pressure gradient Pgrad, Nusselt number Nu, objective function Objektive
- Adaptive Meta Model of Optimal Prognosis (AMOP) identifies with sensitivity analysis influence of GEKO parameters on the simulation's results (responses) and measurement of forecast quality of the response variation



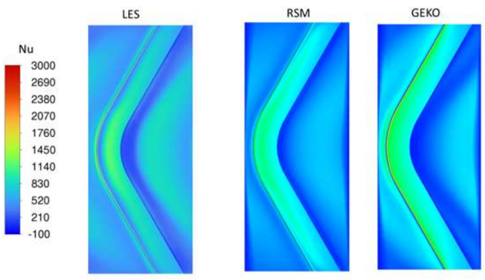
Rib e = 4 mm, AMOP Iterations, best GEKO parameters in design 171



Nusselt number bottom wall for rib e = 9 mm

	Nu	Nu/ Nu0	dev. Nu to Nu LES %	P grad. [Pa/m]	dev. P grad. to P grad. LES %	Darcy fric. factor f	f/f0	dev. Obj. %
LES e = 0.4 mm	626	2.58		-46866		0.050	3.04	
LES e = 0.6 mm	595	2.45		-66889		0.071	4.34	
LES e = 0.9 mm	573	2.36		-80771		0.086	5.24	
RSM e = 0.4 mm	549	2.26	-12.35	-57860	23.46	0.062	3.76	26.51
RSM e = 0.6 mm	554	2.28	-6.82	-68539	2.47	0.073	4.45	7.25
RSM e = 0.9 mm	443	1.82	-22.63	-78175	-3.21	0.083	5.07	22.85
Geko e = 0.4 mm	620	2.55	-1.03	-47946	2.30	0.051	3.11	2.52
Geko e = 0.6 mm	611	2.52	2.72	-70233.7	5.00	0.075	4.56	5.69
Geko e = 0.9 mm	589	0.00	2.84	-78049	-3.37	0.083	5.07	4.41

Table 1: Comparison Results for RSM and GEKO for different rib heights



Nusselt number bottom wall for rib e = 4 mm

Conclusion

- RSM shows lower values of the heat transfer vs. the LES in all cases. The under-estimation of heat transfer was up to 22 %.
- But RSM shows a good match of the values for the friction factor for the higher ribs 0.6 and 0.9 (here max difference 3 %), capture flow features better.
- GEKO (best parameter set was used in each case) match heat transfer and friction factor vs. the LES with a maximal difference of 5 %.
- Baseline (BSL) Reynolds Stress Model (RSM) with the GEKO options seems promising capturing flow features and with the tuneable GEKO able to solve challenges regarding turbulent heat transfer.

EUROfusion

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