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VERIFICATION AND VALIDATION SYMPOSIUM

# Code Verification of ReFRESCO using the Method of Manufactured Solutions

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## Contents

1. Introduction

- Development of a reliable CFD solver requires thourough Code Verification to guarantee the correctness of the code and to assess its grid and time-step convergence properties

- Code Verification of a (U)RANS solver requires the use of the Method of the Manufactured Solutions to allow the evaluation of discretization errors

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2. Manufactured Solutions

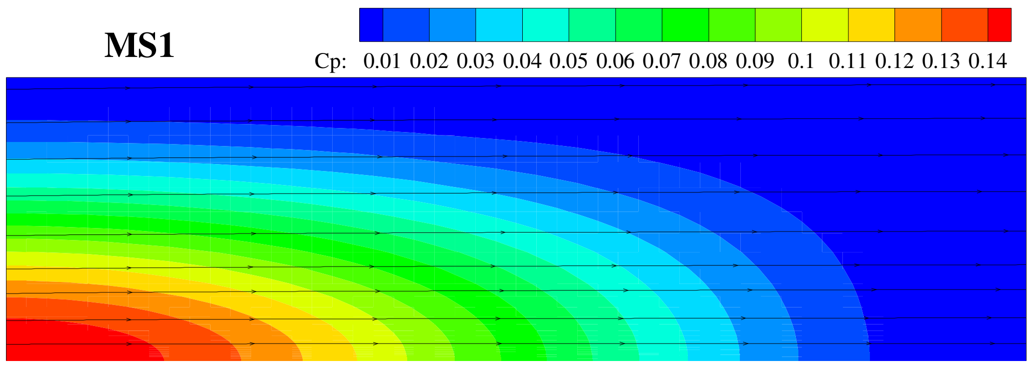
- Two-dimensional solutions that mimic near-wall, statistically-steady, incompressible flows

- Flow field includes a “linear sub-layer” for $y^+<5$ and the “skin friction coefficient” at the wall matches an empirical correlation for a flat plate turbulent boundary-layer

- Turbulence quantities of eddy-viscosity models are also manufactured (but not used in the present exercise)

## 2. Manufactured Solutions

**MS1**

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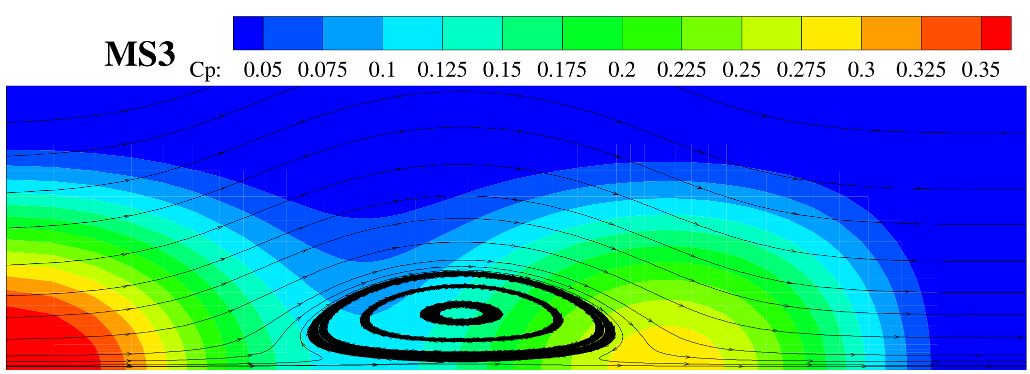
## 2. Manufactured Solutions

**MS3**



3. ReFRESCO

- URANS solver with a fully-collocated arrangement and a face-based data structure
- Finite-volume discretization in the physical space
- Able to handle volumes of arbitrary shape, which means that it is suitable for complex geometries
- Preserving second-order grid convergence (at internal and boundary cells) is a challenge

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4. Non-orthogonality corrections

- Diffusion term of general transport equation

$$-\int_S \Gamma\left(\vec{\nabla}\phi \cdot \vec{n}\right) dS$$

- Finite-volume discretization

$$-\int_S \Gamma\left(\vec{\nabla}\phi \cdot \vec{n}\right) dS \cong -\sum_{j=1}^{n_{faces}} \Gamma_{f_j} \left(\vec{\nabla}\phi \cdot \vec{n}\right)_{f_j} S_{f_j}$$

4. Non-orthogonality corrections

- Present work focus on the determination of the normal derivative of a variable $\phi$ at a face

$$\left(\vec{\nabla}\phi\cdot\vec{n}\right)_{f_j}=\vec{\nabla}\phi_{f_j}$$

- Second-order accurate determination of $\vec{\nabla}\phi_{f_j}$ is supposed to use only the values at the two neighbouring cell faces

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4. Non-orthogonality corrections

- Interpolation of $\vec{\nabla}\phi_{f_j}$

$$\left(\frac{\partial\phi}{\partial n}\right)_f=\vec{\nabla}\phi_f\cdot\vec{n}_f=\vec{\nabla}\phi_f\cdot\left(\vec{\Delta}_o+\vec{\Delta}_n\right)$$

$$\left(\frac{\partial\phi}{\partial n}\right)_f=\left(\frac{\phi_{c2}-\phi_{c1}}{d_o}\right)^n+\left(\vec{\nabla}\phi_f\cdot\left(\vec{n}_f-\vec{\Delta}_o\right)\right)^{n-1}$$

$$\left(\frac{\phi_{c2}-\phi_{c1}}{d_o}\right)\cong\vec{\nabla}\phi_f\cdot\vec{\Delta}_o$$

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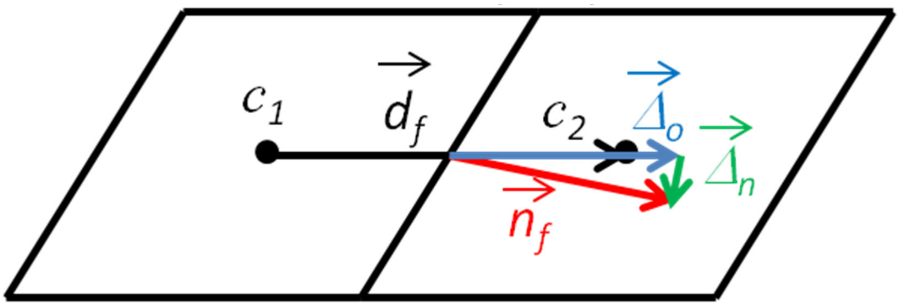
4. Non-orthogonality corrections

- Interpolation of $\vec{\nabla}\phi_{f_j}$

$$\vec{n}_f = \vec{\Delta}_o + \vec{\Delta}_n, \quad \vec{\Delta}_o = \frac{1}{d_o}\vec{d}_f$$

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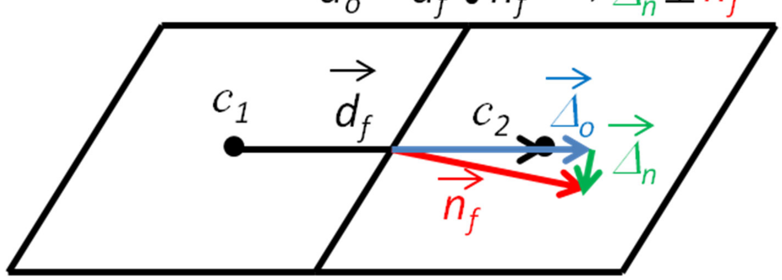
4. Non-orthogonality corrections

- Interpolation of $\vec{\nabla}\phi_{f_j}$ , TYPE 1

$$\vec{n}_f = \vec{\Delta}_o + \vec{\Delta}_n, \quad \vec{\Delta}_o = \frac{1}{d_o}\vec{d}_f$$

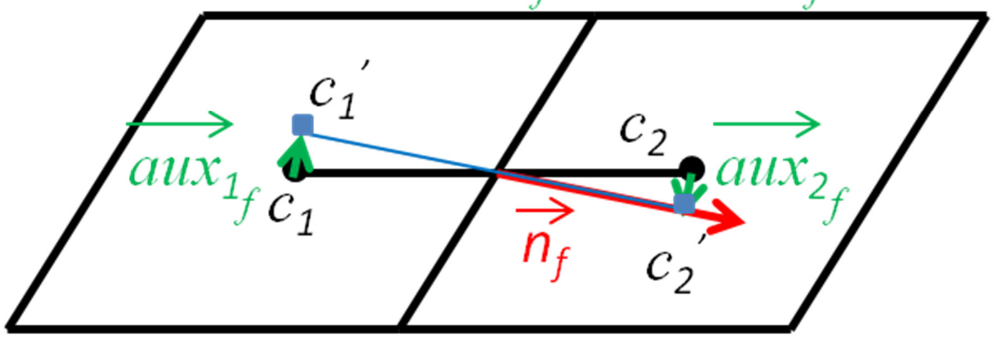
$$d_o = \vec{d}_f \bullet \vec{n}_f \Rightarrow \vec{\Delta}_n \perp \vec{n}_f$$



4. Non-orthogonality corrections

- Interpolation of $\vec{\nabla}\phi_{f_j}$ , TYPE 2

$\overrightarrow{aux_{1_f}} \perp \vec{n}_f \quad \overrightarrow{aux_{2_f}} \perp \vec{n}_f$

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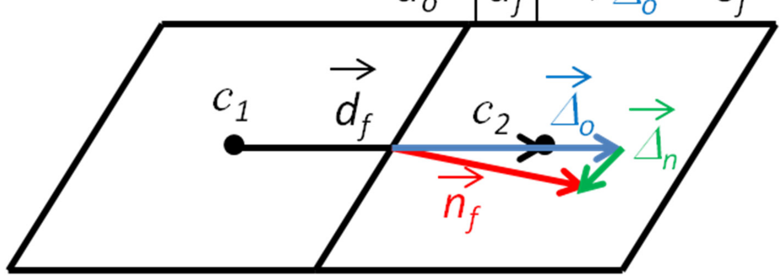
4. Non-orthogonality corrections

- Interpolation of $\vec{\nabla}\phi_{f_j}$ , TYPE 3

$$\vec{n}_f = \vec{\Delta}_o + \vec{\Delta}_n, \quad \vec{\Delta}_o = \frac{1}{d_o}\vec{d}_f$$

$$d_o = \left|\vec{d}_f\right| \Rightarrow \vec{\Delta}_o = \vec{s}_f$$

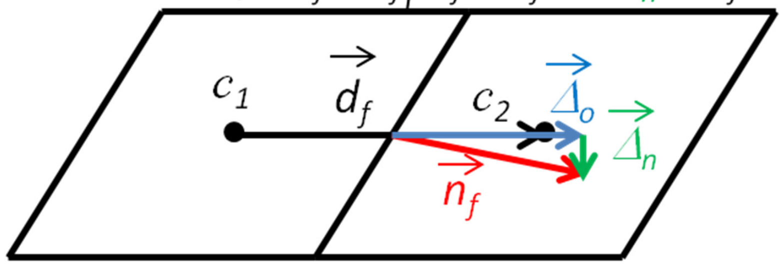


## 4. Non-orthogonality corrections

- Interpolation of $\vec{\nabla}\phi_{f_j}$ , TYPE 4

$$\vec{n}_f = \vec{\Delta}_o + \vec{\Delta}_n, \quad \vec{\Delta}_o = \frac{1}{d_o}\vec{d}_f$$

$$d_o = \vec{d}_f \bullet \vec{d}_f \big/ \vec{d}_f \bullet \vec{n}_f \Rightarrow \vec{\Delta}_n \perp \vec{d}_f$$

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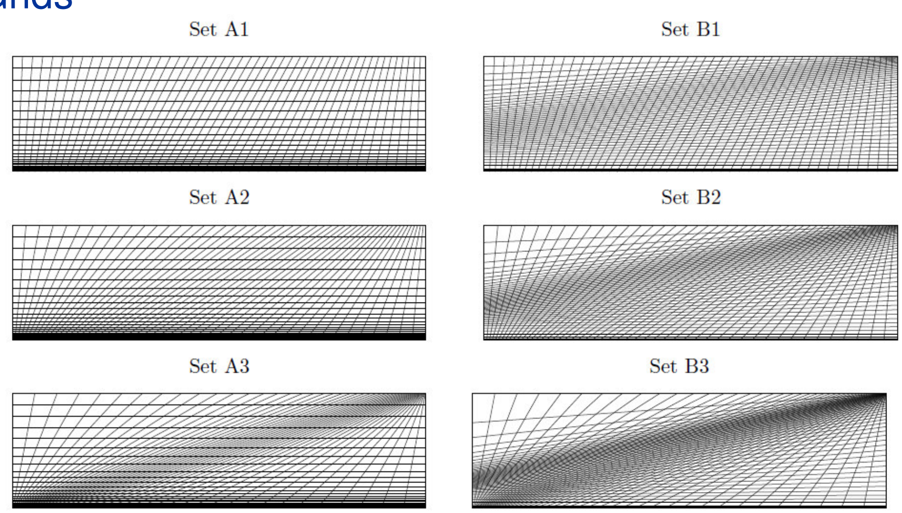
## 5. Results

- Grids



## 5. Results

- Grids

| Grid Set | Internal Faces | | Horizontal Boundary Faces | | Vertical Boundary Faces | |
|---|---|---|---|---|---|---|
| | $\delta^o_{max}$ | $\delta^o_{avg}$ | $\delta^o_{max}$ | $\delta^o_{avg}$ | $\delta^o_{max}$ | $\delta^o_{avg}$ |
| A1 | 29 | 20 | 29 | 20 | 0 | 0 |
| A2 | 55 | 40 | 55 | 40 | 0 | 0 |
| A3 | 70 | 56 | 70 | 56 | 0 | 0 |
| B1 | 35 | 23 | 29 | 20 | 6 | 3 |
| B2 | 63 | 45 | 55 | 40 | 8 | 4 |
| B3 | 80 | 60 | 70 | 56 | 10 | 5 |

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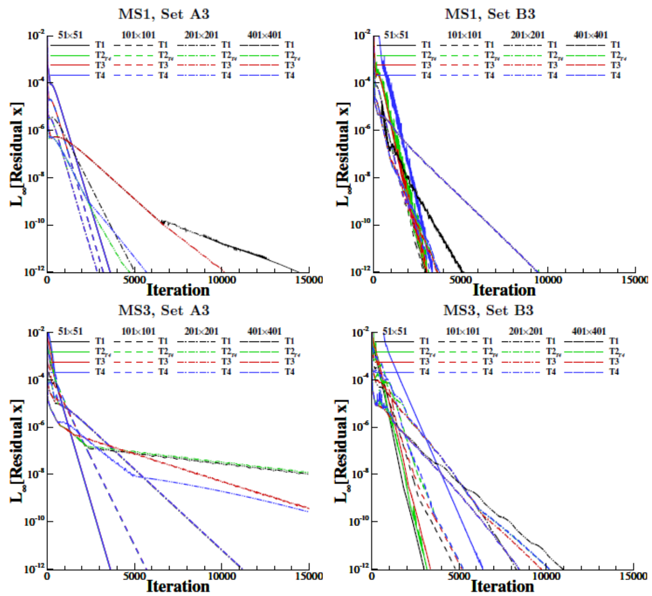
## 5. Results

- Determination of $L_2$ and $L_\infty$ norms of the errors of mean flow quantities $(u_x, u_y, C_p)$
- Observed order of grid convergence and error constants determined from data of six finest grids
- Second-order QUICK scheme in convection
- No excentricity issues for present grid sets

## 5. Results

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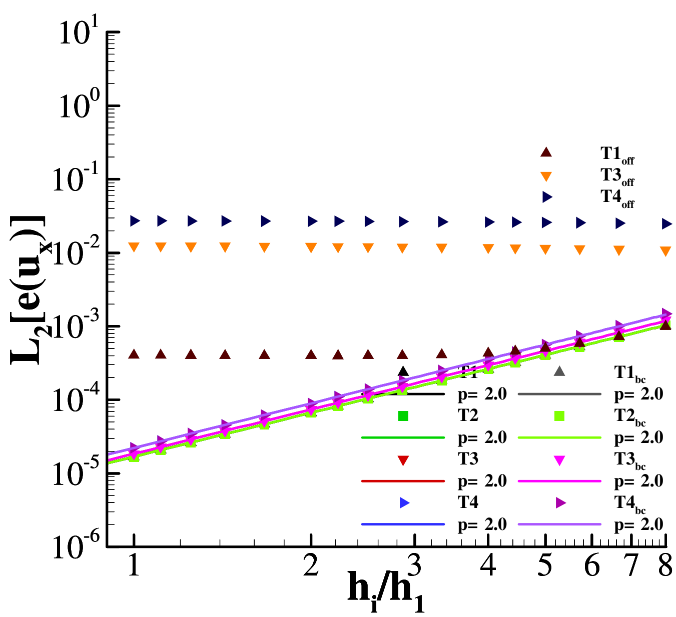
## 5. Results

MS1, Set A2



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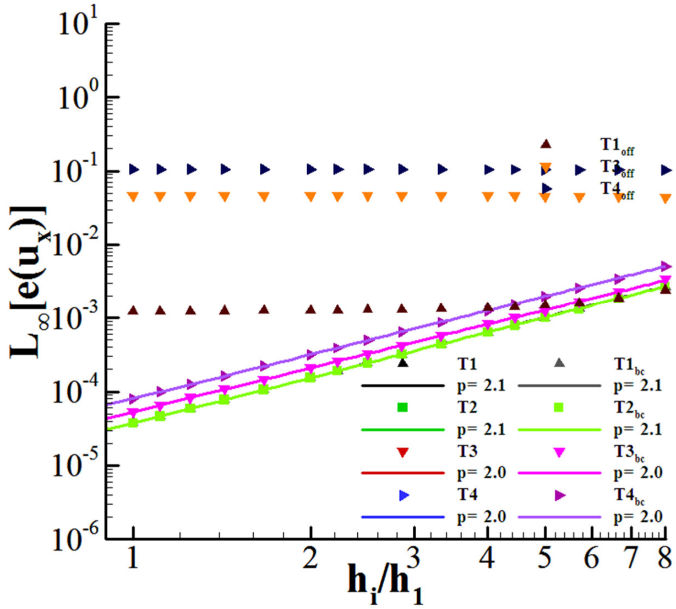
## 5. Results

MS1, Set A2

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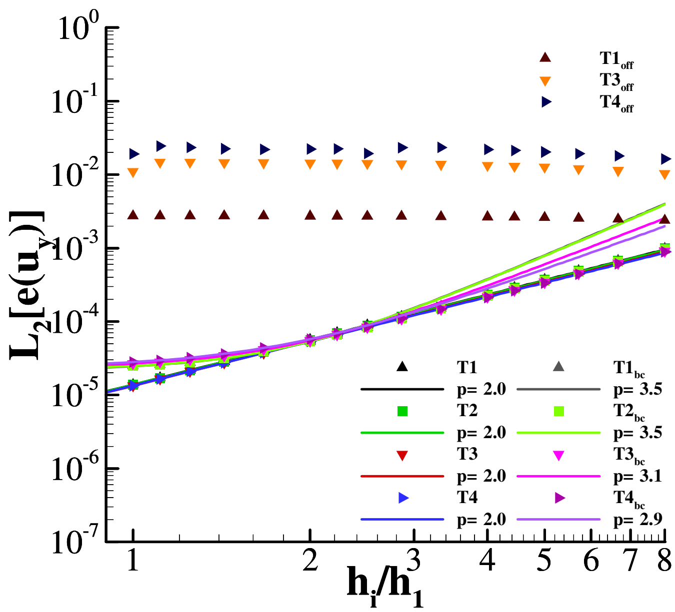
## 5. Results

MS3, Set A2



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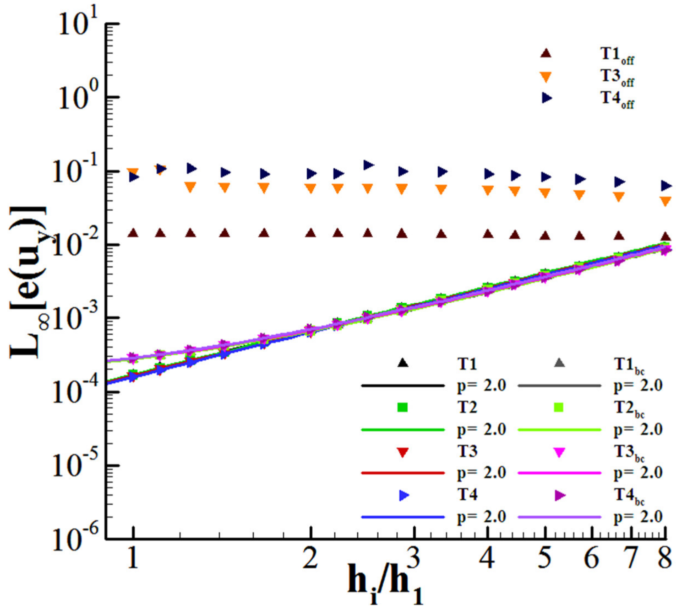
## 5. Results

MS3, Set A2

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## 6. Conclusions

- Non-orthogonality corrections are mandatory to obtain a consistent discretization scheme
- Non-orthogonality should also be corrected at boundary faces. However, the “boundary error” may be negligible
- Thorough Code Verification is essential for the credibility of any CFD code