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CFD APPLIED TO DEAD-END ANALYSIS IN HYGIENIC FOOD PROCESSING SYSTEMS

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INTRODUCTION

One of the main issues regarding the hygienic design of closed equipment and piping systems for food processing is the ubiquitous presence of dead-ends, no matter how carefully they may be designed. These dead-ends present huge risks from the food safety standpoint (chemical and biological contamination), and clear challenges for in-place cleaning and sterilization procedures.

Computational fluid dynamics (CFD) has been proven as a valid and robust tool to model and simulate flow problems in many different areas, including the design and analysis of different food processing equipment and processes (Jensen, 2003; Jensen *et al.*, 2005).

Our main aim in this contribution is the systematic assessment of dead-ends through modelling and simulation using CFD tools, including the analysis of different dead-end´s geometries, flow configurations, as well as the impact of food rheology. Another outcome of our analysis is the prediction of pressure or head losses associated with some alternative accessories that may improve the hygienic design and performance of food processing systems.

BACKGROUND

International associations that lead the development of standards for hygienic engineering and design, like the European Hygienic Engineering and Design Group (EHEDG) and 3-A Sanitary Standards, Inc. (3-A SSI), have established their own recommendations for the dead-ends aspect ratio (length/diameter or L/D ratios). Even when both associations agree in the geometrical definition of L and D parameters, they differ regarding the maximum acceptable numerical values.

Whereas EHEDG has established a maximum value for L/D ratio of 1 for any situation, 3-A SSI (2018) states an L/D ratio maximum of 2 (never exceeding 5 inches, or 127 mm, in length), including some remarks about how to handle protrusions located within the dead-end (e.g. thermowells).

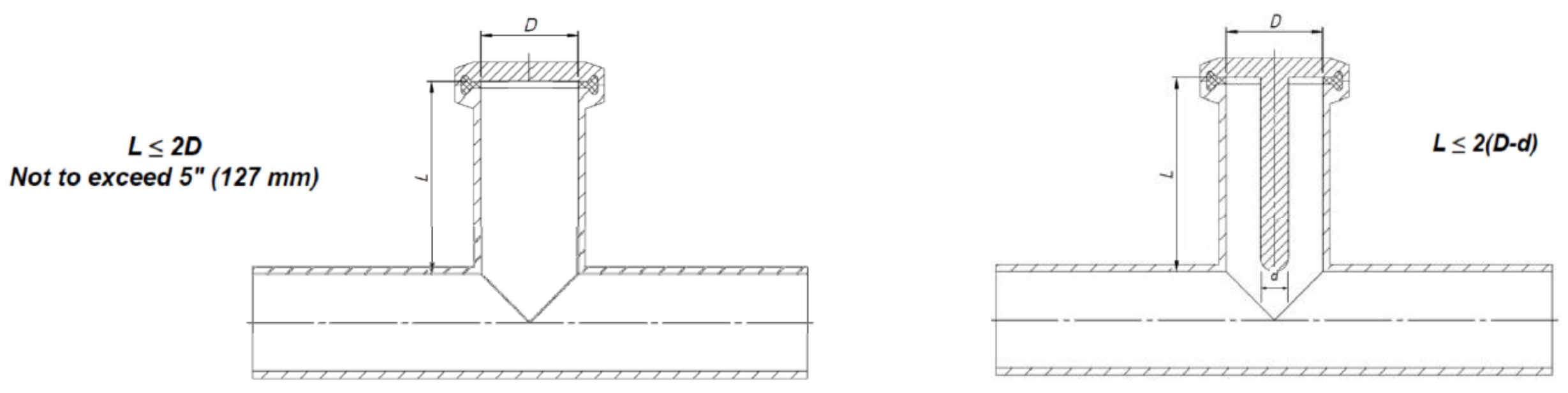

Figure 1. 3-A SSI standard requirements for dead-ends (Source: 3-A SSI, 2018).

Another recommendation from EHEDG (2007) to improve the hygienic performance is the installation of swept-tees (sometimes called seagull-tees) whenever necessary, instead of right angle straight-tees (Figure 2). Even in this situation, the EHEDG requires a maximum dead-end L/D ratio ≤ 1, which may seem to be too restrictive, because their geometry partially diverts the flow inside the stagnant zone and therefore may increase the turbulence inside this critical area.

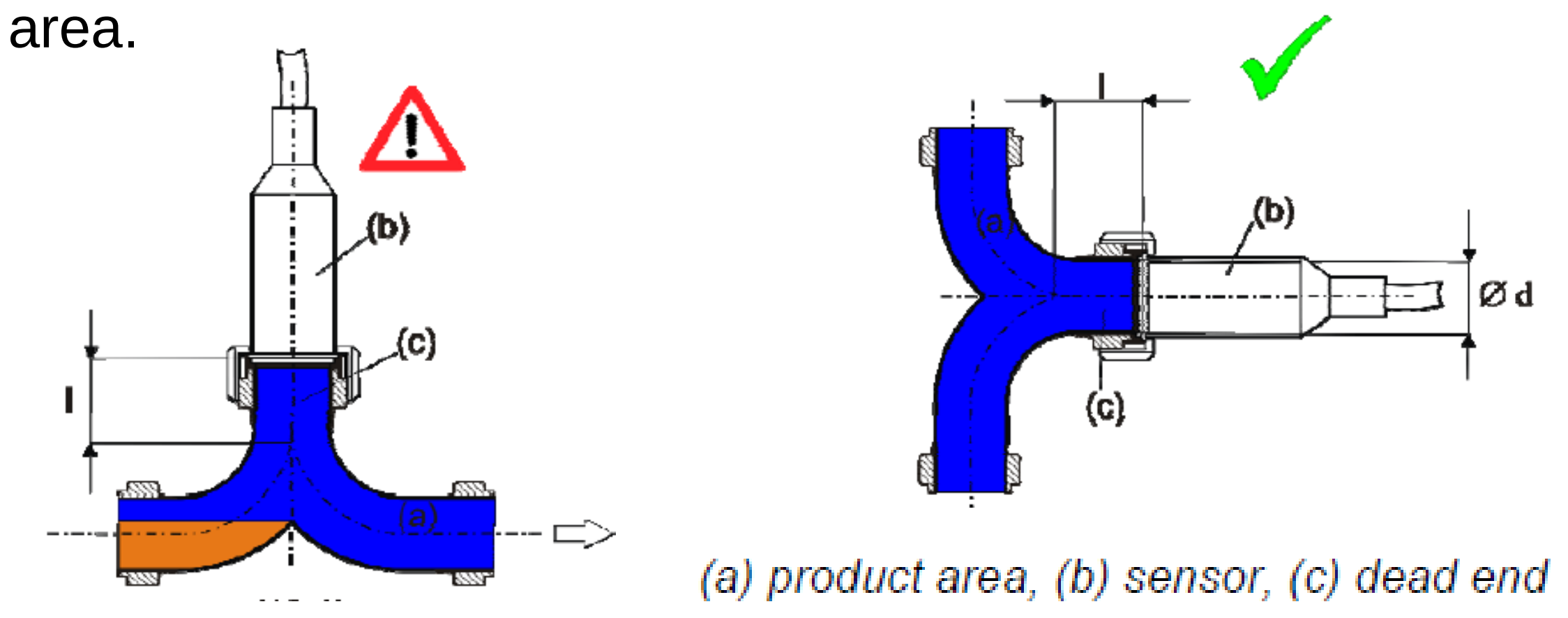

Figure 2. EHEDG guidelines for use of swept-tees to avoid dead-ends (Source: EHEDG, 2007).

Graßhoff (1980) published one of the first and few experimental studies regarding the fluid motion inside the stagnant zones present in dead-ends, both in relation to the rinsing behaviour (fluid exchange between the main and branched pipe) and cleaning behaviour (local wall shear stress). However, his analysis was done only with right angle straight-tees and just one flow configuration.

Unfortunately, there are no available published data regarding the hygienic performance of swept-tees during rinsing and/or cleaning procedures, nor any recommendation about maximum L/D ratio for this type of accessories. Besides that, the hydraulic head loss equivalent factor associated with this type of fitting is not readily available in the literature.

Therefore, we believe there are several issues regarding dead-end analysis that still require further studies, in order to improve the hygienic performance of closed food processing systems.

MATERIALS AND METHODS

All fluid domains were modelled as 3D solid bodies using the parametric CAD/CAE software SolidWorks® Premium 2014 x64 Edition (SP3.0) from Dassault Systèmes. As these type of fittings are not included in avaliable international standards (e.g. DIN 11852), dimensions were taken from suppliers´ catalogues for standard hygienic stainless-steel fittings (right angle straight- and swept- and seagull-tees).

Meshing of these flow domains, together with model building and numerical simulations were carried out using the Finite Element Analysis software COMSOL Multiphysics® v5.2a from COMSOL Inc. (with CFD and Chemical Reaction Engineering modules). Meshes consisted of tetrahedral elements, with physics-controlled refinement, allowing better resolution at fittings´ sharp edges (approx. 3.195.000 elements).

The flow model used was incompressible, fully three-dimensional, continuity and Reynolds Averaged Navier-Stokes (RANS) equations, coupled with a standard k-ε turbulence model. Boundary conditions were set for inlet (average flow velocity) and outlet (zero pressure). The flow near walls was modelled using wall functions (δ_W).

***Mathematical model equations**:*

$$\rho\frac{\partial \mathbf{U}}{\partial t} + \rho\mathbf{U}\cdot\nabla\mathbf{U} + \nabla\cdot\overline{(\rho\mathbf{u}'\otimes\mathbf{u}')} = -\nabla P + \nabla\cdot\mu(\nabla\mathbf{U} + (\nabla\mathbf{U})^T) + \mathbf{F}$$

$$\rho\nabla\cdot\mathbf{U} = 0$$

$$\rho\frac{\partial k}{\partial t} + \rho\mathbf{u}\cdot\nabla k = \nabla\cdot\left(\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right) + P_k - \rho\varepsilon$$

$$\rho(\overline{\mathbf{u}'\otimes\mathbf{u}'}) - \frac{\rho}{3}\mathrm{trace}(\overline{\mathbf{u}'\otimes\mathbf{u}'})\mathrm{I} = -\mu_T(\nabla\mathbf{U} + (\nabla\mathbf{U})^T)$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho\mathbf{u}\cdot\nabla\varepsilon = \nabla\cdot\left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}$$

$$\mu_T = \rho C_\mu\frac{k^2}{\varepsilon}$$

$$P_k = \mu_T\left(\nabla\mathbf{u}:(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - \frac{2}{3}(\nabla\cdot\mathbf{u})^2\right) - \frac{2}{3}\rho k\nabla\cdot\mathbf{u}$$

RESULTS

Figure 3 shows an example for the geometry and mesh used for a seagull-tee (2 inches OD size, comprised of two 90° ISO bend elbows), with a L/D value of 1.7 (L measured from the internal surface of the horizontal section). Also, some results for the fluid velocity and pressure profiles are shown, using an inlet mean flow velocity of 2 m/s.

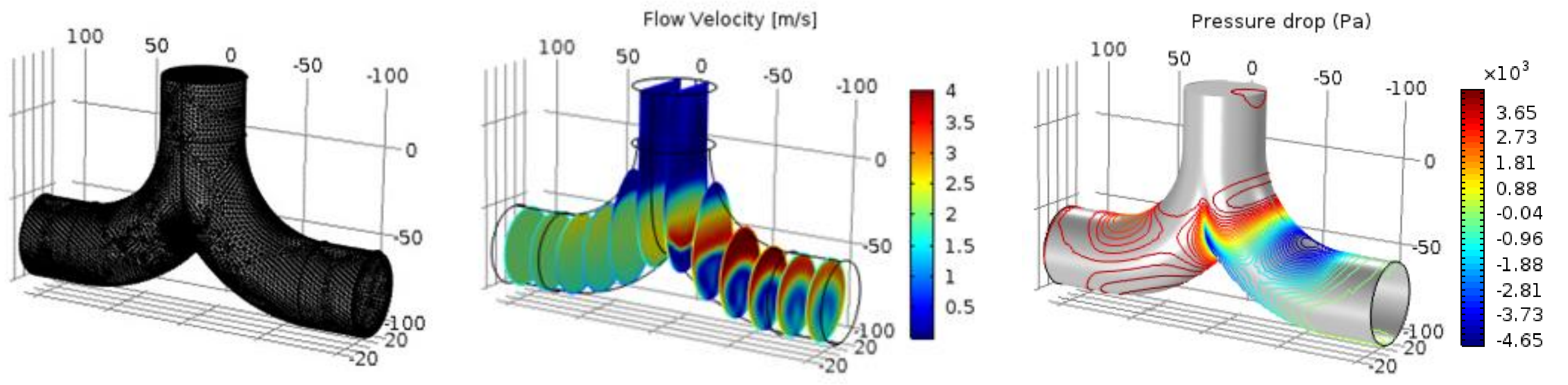

Figure 3. Seagull-tee flow domain mesh, flow velocity and pressure drop profiles.

We found that the flow velocity drop inside the stagnant zone is very significant, achieving approximately 15 % of the inlet mean flow velocity (U_0). The flow velocity drop computed is almost the same for an inlet flow velocity in the range from 1 to 4 m/s. These findings are consistent with the experimental data published by Graßhoff (1980) for straight-tees with a L/D ratio of 1.0.

Moreover, averaged wall shear-stresses computed from the mathematical model on the top and lateral surfaces of the dead-end showed values below 0.15 Pa, consistent with low velocity recirculation zone. These wall shear-stress values are well below the recommended figures to assure a correct surface cleaning effect in pipes (> 0.40 Pa).

CONCLUSIONS

Our preliminary results show that flow behaviour inside the stagnant zone of swept-tees is far more complex than in straight-tees, and requires more computational effort to achieve stable simulation results.

Reduced flow velocities and shear-stresses inside dead-ends introduced by this kind of fittings must be carefully assessed, since turbulence intensity introduced by round shapes may not be high enough to assure a higher cleaning effect when compared to straight-tees.

Standard sizes for these fittings available from worldwide recognized suppliers use to have higher L/D aspect ratios than recommended by hygienic design organizations. Some improvements for EHEDG (2007) guidelines may be necessary when specifying and suggesting the installation of swept-tee type fittings, e.g. length measurements and protrusions within the stagnant zone.

Future work will focus on the transport of diluted species inside these type of dead-ends in order to assess the performance of different geometries on mass transfer rates, and their impact on rinsing step time during cleaning operations.

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