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RESIDENCE TIME DISTRIBUTION CONTROL IN ASEPTING PROCESSING USING A BYPASS HOLDING TUBE

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In the present work the possibility of accelerating the slowest particles in aseptic processing in order to reduce the Resident Time Distribution (RDT) distribution is investigated.
Using an appropriate geometrical configuration of a bypass holding tube, particle in the lower zone of the principal tube are driven by a pressure gradient in a secondary tube where they are accelerated and reinserted in the principal one with an higher value of kinetic energy.

1. INTRODUCTION

The concept of aseptic processing originated to solve problems associated with conventional 'in-container' sterilization of foods such as low rate of heat penetration to the slowest heating point in the container, the long processing times required to deliver the required lethality, destruction of the nutritional and sensory characteristics of the food, low productivity, and high energy costs (Smith et al., 1990).
Aseptic processing technique has been successfully applied to liquid foods and acid foods containing discrete particulates.
However, the extension of aseptic processing to heterogeneous low-acid liquid foods containing discrete particulates has been difficult due to lack of data on critical factors such as interfacial heat transfer coefficient between the liquid and the particle as well as the residence time distribution of particles in the holding tube of the aseptic system.
Geometry of holding tube represents a primary parameter in determining the residence time distribution (RTD) of particulate inside an aseptic processing system.
Several configuration had been investigate in the past, including curved geometries in order to maximize mixing of particle inside the holding tubes and minimize the widening of RTD.
The presence of particles travelling near the bottom of the tube in the boundary layer, i.e. in the low velocity zone is a factors influencing RTD.

2. PROCESS AND PARTICLE VARIABLES

Several process and particle variables are involved in aseptic processing of particulate, and it is far from the purpose of this paper to provide an extensive description of mutual interaction between themselves.
Among them:
1) tube orientation;
2) tube diameter;
3) flow rate;
4) tube geometry;
5) particle size, shape and density;
6) particle concentration.

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Phenomena involved in transport mechanisms of particles are rather complex, involving buoyancy effects, wakes and boundary layer, and particles-particles and tube-particles collisions.
An interesting effect which appears in a conventional (near horizontal) tube operating under low particle concentrations and low fluid viscosity is a sedimented layer stratification due to buoyancy effects (see fig. 1).

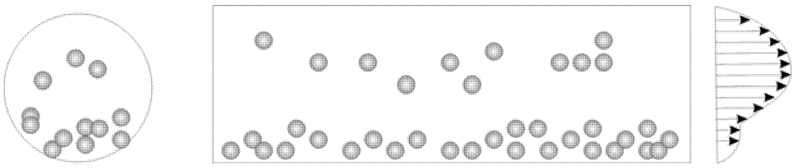

Figure 1. Channeling, sedimented layer and decreased effective cross sectionat low particle concentration.

The presence of sedimented layer at the bottom of the tube can cause a flow channeling in upper zone, resulting in a wider residence time distribution (Dutta e Sastry, 1990 a,b, Fregert, 1995), and the effect appears maximum with a particle concentration of 10-20% (Liu et al.,1993).
A possible solution to this problem is the use of a secondary bypass tube collecting slow traveling particles at the bottom and accelerating them in order to reduce their residence time respect to the particles travelling in the fully developed velocity profile in the centre of the holding tube.

3. MATERIALS AND METHODS

The design of the bypass tube was obtained by using a numerical approach. A control volume simulation code (Fluent Inc. 6.3.26) was used in a 3D configuration, coupled with a collision detection algorithm in order to model particles interactions.
In the preliminary work, described in this paper, the principal target was the design of the bypass tube.
The 6 degree of freedom motion of the particle is computed by solving the Newton-Euler equations for rigid-body motion.
The motion is broken into a translation of the center of mass (c.m.) of the body (Newton's equations), and a rotation about a centroidal axis system attached to the body (Euler's equations)
The moving mesh approach was adopted in the simulations: the particle was modeled as a moving rigid sphere with 3 translational and 3 rotational degrees of freedom, driven by hydrodynamic pressure and shear forces computed in a time dependent numerical code.
The body state vector is comprised of the inertial position components of the body mass center (x,y,z), the standard sequence Euler angles (φ, θ,ψ), the body frame components of the mass center velocity (u,v,w), and the body frame components of the angular velocity vector (p,q,r).

The standard body frame equations of motion are given by

$$\begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{Bmatrix} = \begin{bmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \tag{1}$$

$$\begin{Bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{Bmatrix} = \begin{bmatrix} 1 & s_\phi t_\theta & c_\phi t_\theta \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi / c_\theta & c_\phi / c_\theta \end{bmatrix} \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} \quad \textbf{(2)}$$

$$\begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{Bmatrix} = \begin{Bmatrix} F_x / m \\ F_y / m \\ F_z / m \end{Bmatrix} \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \quad \textbf{(3)}$$

$$\begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix} = [I]^{-1} \left[\begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix} - \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} [I] \begin{Bmatrix} p \\ q \\ r \end{Bmatrix} \right] \quad \textbf{(4)}$$

Where $c_\phi = \cos\phi, s_\phi = \sin\phi, t_\phi = \tan\phi$, and **F** and **M** are the forces and moments vectors computed in body coordinates.
The applied force acting on the center of mass has been broken into three components; the aerodynamic forces computed by the numerical solver $\mathbf{F}_a$, the external applied forces (such as impulses due to collisions) $\mathbf{F}_e$, and the forces due to gravity $\mathbf{F}_g$.

$$\mathbf{F}_t = \mathbf{F}_a + \mathbf{F}_e + \mathbf{F}_g \quad \textbf{(5)}$$

An partial inelastic collision model was adopted with a coefficient of restitution of 0.9; this coefficient was assumed in an heuristic way on the hypothesis that a small elastic deformation could occur during impact, resulting in a loss of kinetic energy.
A numerical difficulty to overcome was to develop a collision detection algorithm to be used in the numerical simulation, as in a real situation the collision would require a zero volume control volume at collision time between the colliding particles or the tube, resulting in an error in the numerical simulation.
To this purpose, a computational boundary layer BL was inserted around each particle: in this way the collision was assigned when in the projected trajectory the BL is supposed to collide with another boundary as described in Fig. 2.
Choosing an appropriate time step Δt in order to skip the exact collision time t_0, the particle position was then reassigned in the new trajectory and with new post impact velocities.

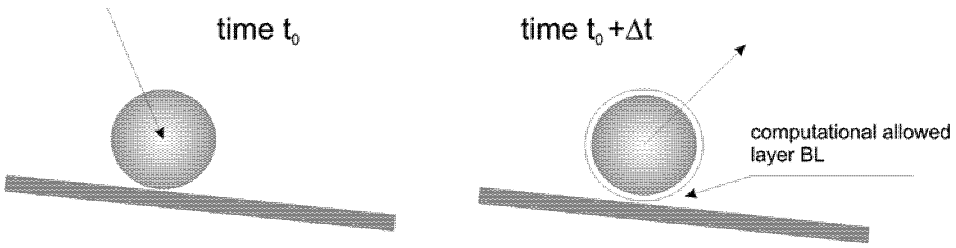

Figure 2. Collision detection algorithm: computational layer BL .

The height of this computational layer was chosen by using an impulse approach based on trajectory tracking and collision prediction, considering numerical requirements to reduce interpolation errors in the moving mesh approach and to reduce the error due to the forced collocation of the particle in the new position and trajectory.
In order to capture particles at the bottom of the principal tube, a particular design of the bypass tube was obtained (see fig. 3b) starting from fig. 3a configuration and using an Optimal Shape Design approach, a numerical technique (Anagnostou et al., 1992; Mohammadi and Pironneau, 2001; Pironneau, 1984) allowing an automatic design of an optimal functional shape.
In such approach, the solution is obtained by coupling together a discrete model of the process parameters, in this case obtained by solving the Navier-Stokes equations for a non-newtonian fluid, including the geometrical shape as a part of the degrees of freedom of the problem, and a constrained multivariate minimization algorithm is used in order to minimize an objective mathematical function describing the efficiency of the process.

In this case the angle of insertion of the lower tube B1 and the tube insertion diameter was optimized in order to maximize the pressure gradient due to the Venturi effect between the upper and lower tubes in proximity of the hole C1.
The presence of a convergent-divergent section C2 in the upper tube enhances the pressure rise in the zone behind the connection hole C1.

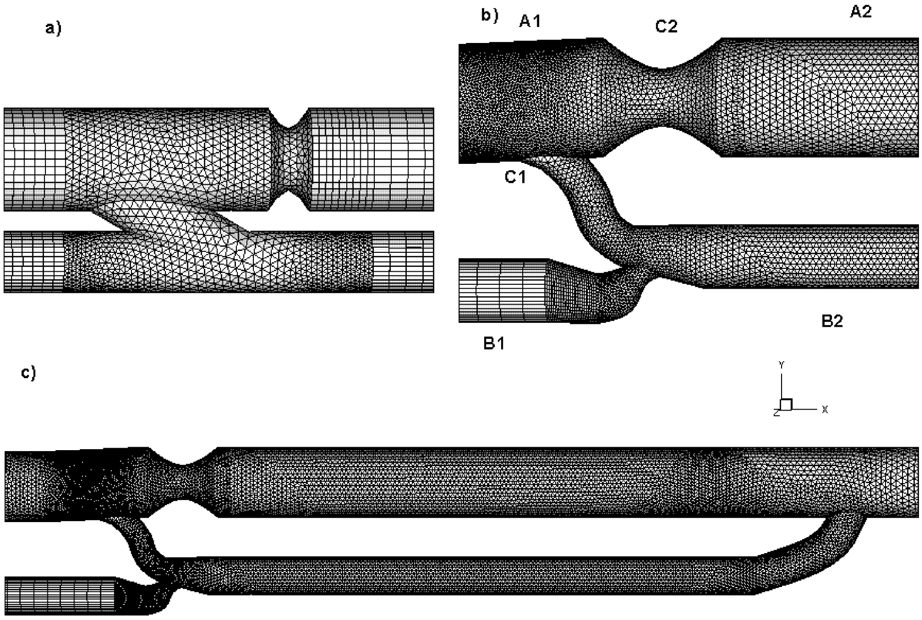

Figure 3.Initial (a) and final (b) configuration of bypass holding tube (c) after optimization.

4. TEST CONFIGURATION

Results shown are referred to the following test configuration: transported particles are green pees with 0.006 m diameter, density equal to 1060 Kg/m^3, inlet velocity V1 in the upper tube equal to 0.5 m/s (flow rate 21 l/min) and V2 in the lower tube set to 0.7 m/s (flow rate 8.4 l/min).
The upper tube diameter was set to D1=0.03 m and the bypass one D2=0.017 m, and the bypass tube length is 0.35 m. The carrier fluid viscosity was modelled as a 0.5% solution of aqueous solution of sodium

carboxymethylcellulose, with a power-law viscosity with the values for K and n set to 0.297 Pa s^n and 0.7025, respectively.

5. RESULTS AND CONCLUSIONS

In Fig 4 local differential pressure (Pa) and vector velocity distribution in a mid-plane in the bypass holding tube zone is shown, highlighting the pressure gradient and bypass flow rate from the upper tube at slower velocity to the bypass one.

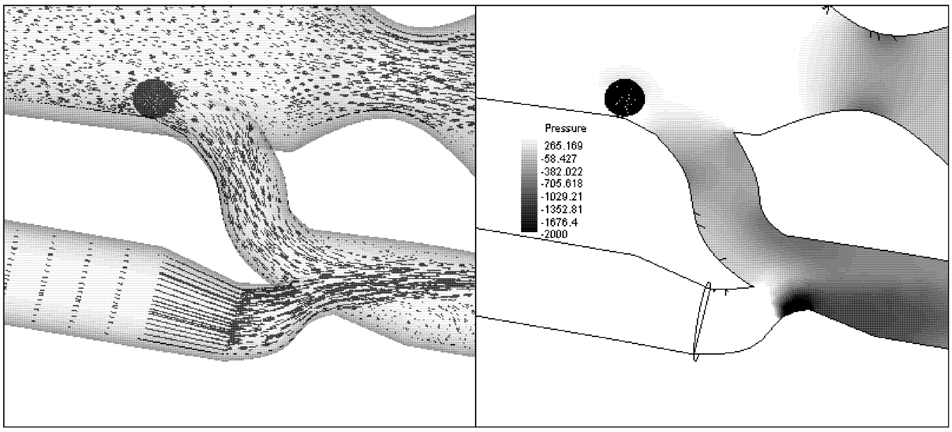

Figure 4.Vector velocity distribution and relative (gauge) pressure field on a normal section in the bypass holding tube zone.

The particle, driven by hydrodynamic and gravitational forces (see sequence in Fig. 5 a-f), was pushed into the bypass holding tube and then accelerated by the higher average velocity.
The computed bypass tube residence time t_1 was globally 0.28 s, compared with t_2= 0.76 necessary to travel the same distance for particles travelling at the centre in the upper tube .

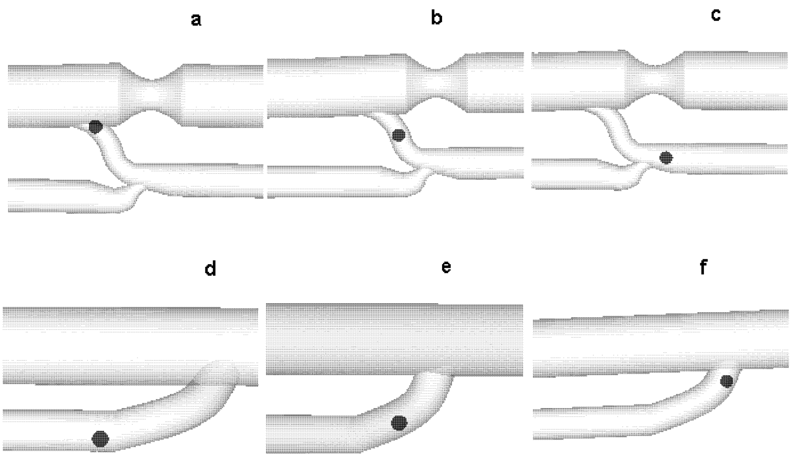

Figure 5. Particle position at different time step in the entrance and leaving zone of the bypass tube.

The previously showed numerical results were compared with experimental data, not presented in this work and obtained on a laboratory scale equipment reproducing the geometry in Fig. 3c, confirming what was found numerically.
These preliminary results in a test tube section showed the possibility of controlling RTD by using an appropriate geometrical configuration of the holding tubes. In order to generalize the obtained results a wider range of process and particles parameters need to be investigated.

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