CFD simulation of convective heat transfer in vessel with mechanical agitation for milk

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Abstract Computational fluid dynamics (CFD) analysis using ANSYS Fluent software has been carried out to investigate velocity profiles and thermal characteristics of milk during heating under mechanically agitated condition. In earlier article experimental data on forced convection heat transfer coefficient ($\bar{h}$) and correlations of the form $Nu = a \cdot Re^b \cdot Pr^{0.33}$ for cow milk, standardised milk and full cream milk in Baffled vessel and Unbaffled vessel with scraping, using Propeller, Flat Six Blade Turbine (FBT), Inclined Six Blade Turbine (IBT) and Paddle impellers were reported. It was noted milk in Baffled vessel with Paddle impeller provided highest $\bar{h}$ even at lower rotational speeds followed by Propeller, FBT and IBT impellers. In Unbaffled vessel with scraping, Propeller provided the

highest $\bar{h}$ followed by FBT and IBT impellers. Hence, the present investigation has been carried out to validate and understand how different velocity of flow currents and their magnitude influence the heat transfer coefficient values in CFD simulation. It also justifies the relative performance of the impellers delineated in the earlier paper. In addition, theoretical values of heat transfer coefficients computed using CFD shows close agreement with experimental values.

Keywords Milk · Stirred vessel · Impellers · CFD simulations · Velocity profiles

Nomenclature

C_{pm}	Specific heat ($\frac{J}{kgK}$)
D_a	Diameter of impeller (mm)
D_t	Diameter of milk vessel (mm)
E	Height of the impeller position from vessel bottom (mm)
W	Width of the impeller blade (mm)
L	Length of the impeller blade (mm)
g	Acceleration due gravity ($\frac{m}{s^2}$)
$\bar{h}$	Forced convection heat transfer coefficient ($\frac{W}{m^2K}$)
H	Milk level in the vessel (mm)
J	Baffle width (mm)
k_m	Thermal conductivity of milk ($\frac{W}{mK}$)
m	Mass of milk (kg)
n	Speed of rotation of impeller (rpm)
Nu	Nusselt number dimensionless ($\frac{\bar{h}D_t}{k_m}$)
p	Pressure ($\frac{N}{m^2}$)
Pr	Prandtl number dimensionless ($\frac{C_{pm}\mu_m}{k_m}$)

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q	Heat transfer by conduction (Watt)
Re	Reynolds number dimensionless $\left(\frac{n}{60}\right)\left(\frac{D^2 \rho}{\mu}\right)$
SS	Stainless steel
t	Vessel thickness (mm), blade thickness (mm) and time (s)
T _m	Milk temperature (K)
T _s	Vessel bottom surface temperature (K)
T _{mo}	Initial temperature of milk (K)
T _{mf}	Final temperature of milk (K)
V	Velocity $\left(\frac{m}{s}\right)$, Volume of milk in the vessel (m ³)
a, b, c, n	Correlation constants in equations
Exptl	Experimental
CFD	Computational fluid dynamics
FBT	Flat six blade turbine

Greek symbol

ρ_m	Density of milk $\left(\frac{Kg}{m^3}\right)$
μ_m	Viscosity of milk $\left(\frac{Kg}{ms}\right)$
τ	Shear stress $\left(\frac{N}{m^2}\right)$
ΔT	Temperature differences (K)

Introduction

Forty-six percentage of milk produced in India is utilised to produce milk based products by thermal processing (Sharma 2006). An earlier article by the author Rajasekaran et al. (2018) reported hitherto undocumented data on forced convection heat transfer coefficient $\left(\frac{-}{h}\right)$ for cow milk standardised milk and full cream milk in vessels with mechanical impellers. It would be quite appropriate to explain the salient aspects of the earlier experimental work, to highlight the importance of present investigation. It was observed that milk: (i) in Baffled vessel with Paddle impeller provided the highest $\bar{h}$ even at lower rotational speeds followed by Propeller, FBT and IBT impellers. (ii) In Unbaffled vessel with scraping, Propeller provided the highest $\bar{h}$ followed by FBT and IBT impellers and (iii) the $\bar{h}$ values decreased with increasing fat contents for the same rpm. In order to establish the underlying influence of flow currents for the relative performance as well as their nature and magnitude, CFD analysis was performed and the results are presented in the current investigation. It would be apt to state at this juncture that there is no documented report of CFD analysis on milk while heating it under mechanical agitation in vessels. Some of the CFD simulation studies focusing on hydrodynamics are given below.

Murthy et al. (2008) carried out CFD analysis of the hydrodynamics in baffled vessel with disc turbine, pitched bladed turbine with blade angles of 60°, 40° and 30° inclination and with hydrofoil impeller. They experimentally verified the CFD data with Laser Doppler Velocimetry and established CFD predictions with experimental results. Ammar et al. (2011) studied the hydrodynamics behaviour of flat bladed turbine, Rushton turbine and Pitched blade turbine using CFD analysis and found that to be in good agreement with experimental results. Achouri et al. (2012) using Fluent software simulated the fluid flow phenomena in agitated tank with turbine and pitched bladed turbine and reported it to be in agreement with experimental data. They also determined power and power number and showed that experimental data and CFD data are in close agreement. Computational fluid dynamics studies and experimental validation have been presented by Chtourou et al. (2011) using standard Rushton turbine in square vessel. Lakghonei et al. (2008) used CFD analysis of liquids while heating by coil and in jacketed vessel in agitated systems with Rushton impeller. They reported higher heat transfer coefficients and more uniform temperature profiles in coil heating systems. Rajasekaran et al. (2014) have reported different designs for Paddle agitator and numerical analyses. Chakravarty (2017) studied the fluid flow and mixing in agitated vessels with pitched blade turbine in turbulent regime. Under specific constraints theoretical values of $\bar{h}$ were calculated and correlations of the form $Nu = a \cdot Re^b \cdot Pr^{0.33}$ was presented.

The objectives of the present investigation are (1) To simulate flow behaviour in milk under heating in the experimental setup explained in the earlier paper (Rajasekaran et al. 2018). (2) To understand and validate in terms of global magnitude of the flow currents generated by the impellers as well as the effect of composition of the milk. (3) To compute theoretical values of heat transfer coefficients and compare with experimental values.

Accordingly, the present investigation reports CFD analysis for three types of milk namely cow milk (3.5% fat), standardised milk (4.5% fat) and full cream milk (6% fat), agitated and heated in vessels with mechanical impellers. These analyses were confined to the following rotational speeds for which high $\bar{h}$ values were reported in the earlier paper. Namely the speeds were set for FBT and Propeller as 150 rpm, for Paddle as 80 rpm in Baffled vessel. Similarly in Unbaffled vessel with scraper, the speeds of FBT and Propeller were set as 80 rpm only. In addition, theoretical values of heat transfer coefficients were computed using CFD and were compared with experimental values.

Fig. 1 **a** Geometry of agitated system with impeller, **b** type of impellers

Geometry of the system

Geometry of the agitated system is presented in Fig. 1a. It consists of Stainless Steel cylindrical vessel (SS) of diameter (D_t) 108 mm with a flat bottom. The milk level (H) is kept equal to the diameter of the vessel. The impeller is placed centrally at a distance (E) of $1/3$ the diameter of vessel. Different type of impellers investigated are shown in Fig. 1b and their geometrical dimensions are given below. Impellers without scraping attachments are used in Baffled vessel, while impellers with scraping attachments were used in Unbaffled vessel. Geometrical parameters of the vessel and different impellers are given below.

S. no	Impeller	D_a/D_t	Pitch	No of blades	W/D_a	L/D_a	E/D_a
1.	Paddle	0.80	—	2	—	—	0.33
2.	Propeller	0.33	1:1	3	—	—	0.33
3.	FBT	0.33	—	6	0.25	0.20	—

Where D_a is diameter of impeller, D_t is diameter of milk vessel, W is width of the impeller blade, L is length of the impeller blade, E is height of the impeller position from vessel bottom.

CFD

Governing equations

CFD analysis was executed to predict the flow and thermal characteristics of milk agitator system based on the following governing equations in vector form.

- I. The continuity equation—mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

where $\vec{v}$ is velocity vector and ρ is the density.

- II. Navier–Stokes equation in the vector format for the conservation of x-momentum, y-momentum and z-momentum.

$$\underbrace{\rho \vec{g}}_{\text{Gravity Force}} - \underbrace{\nabla p}_{\text{Pressure Force}} + \underbrace{\mu \nabla^2 \vec{v}}_{\text{Viscous Force}} = \underbrace{\rho \frac{D \vec{v}}{Dt}}_{\text{Rate of change of momentum}} \quad (2)$$

where $\vec{g}$ —is acceleration due to gravity, p —is pressure.

- III. Energy balance equations

$$\underbrace{-(\nabla \cdot \vec{q})}_{\text{Rate of Energy input by conduction}} - \underbrace{p(\nabla \cdot \vec{v})}_{\text{Rate of internal energy change per unit volume due to pressure}} - \underbrace{(\tau : \nabla \vec{v})}_{\text{Rate of energy loss due to viscous force per unit volume}} = \underbrace{\rho \frac{DU}{Dt}}_{\text{Rate of change of internal energy per unit volume}} \quad (3)$$

The CFD solver code ANSYS Fluent v18 was used for solving these equations. It uses control volume based technique to solve the conservation equations for mass, momentum, and energy balance equations.

CAD model

The CAD model of the system geometry and milk flow volume was the main input information required for CFD

analysis. Consequently, as a first step, the 3D geometry of vessel with agitator was created for three of the impellers viz. FBT, Propeller and Paddle. The accuracy of flow volume extraction plays a vital role in the simulation results, so that dimensions in the real and CFD models are cross-checked and confirmed. A volume extraction of milk with agitator in the vessel was performed before discretisation of geometry.

Discretisation of CFD model

The continuous space of the milk domain was divided into sufficiently small discrete cells called meshing, the distribution of which determines the positions where the flow variables are calculated and stored. Using a mesh of adequate quality is an important part for controlling discretisation errors such as round-off error. Quality check of meshing was executed with significant mesh quality measures such as mesh orthogonality, expansion, and aspect ratio (or stretching). A fine mesh was used near rotating regions of impeller and milk agitation, expecting large variations in the flow variables. The type of mesh used was tetrahedral shaped with an overall quality of 0.94, which is in the accepted limit of CFD solver code Fluent.

Discretisation of the computational domain was performed by a meshing program that uses the approach called Octree—a spatial subdivision algorithm to discretise the flow domain into finite elements—object oriented unstructured meshing. Moreover, Delaunay algorithm was used to create a smoother transition between volume element sizes.

Mesh details

A mesh independence study was followed to avoid the uncertainties in the output results. The mesh size was optimized by conducting grid-independence tests for each impeller model. The mesh size was refined until the analysis results were no longer affected by any further refinement of mesh size. Considering the good agreement with experimental data the mesh count of 3 million was selected as no significant improvement was found beyond this count. Figure 2 shows Mesh model of Baffled and Unbaffled vessel.

To make the milk domain rotate relatively to the rotary movement of impeller, a meshing technique called sliding mesh was used in this analysis. This sliding mesh acts as a rotating reference frame that interacts between stationary

Fig. 2 Mesh model of Baffled and Unbaffled vessel with scraper **a** FBT, **b** Propeller, **c** Paddle, **d** FBT with scraper, **e** Propeller with scraper

milk and rotating impeller. This technique provides the most accurate description of the flow field in unsteady state interactions of milk and rotating agitator. As a time-accurate solution for rotor–stator interaction rather than a time-averaged solution is desired in this study, the sliding mesh model was employed to compute the unsteady flow field and this procedure helped to predict the time required to reach the desired milk temperature.

Input parameters

After attaining the mesh convergence, the properties of different milk used in this study were specified as given below.

Types of milk	Density (ρ_m) kg/m ³ Minim et al. (2002)	Viscosity (μ_m) Pa.s $\times 10^3$ Kessler (2002)	Thermal conductivity (k_m) W/m K Kessler (2002)	Specific heat (C_{pm}) J/kg K Minim et al. (2002)
Cow milk	1022.75	1.50077	0.2823	3819.62
Standardised milk	1022.75	1.50749	0.2851	3819.62
Full cream milk	1022.75	1.51756	0.28722	3819.62

The following input parameters were provided to the CFD analysis.

- Milk is Newtonian fluid.
- At time $t = 0$ Milk is stationary and then rotates at different relative speeds to the impeller.
- For FBT and Propeller the impeller speed input was 150 rpm in Baffled vessel and they were 80 rpm for in Unbaffled vessel. For Paddle, it was 80 rpm.

The computational domain was divided into rotating impeller and non-rotating zones of milk and air on top. The interfaces between milk and impeller are maintained as non-conformal. These interfaces are the surfaces of revolution about the axis of rotation of impeller and rotationally periodic in nature. However, adjacent zones have equal periodic angles. The cell zones of milk and impeller move relative to one another as per the time steps applied. For each time step of agitator rotation, the meshes are moved and the fluxes at the sliding interfaces are recomputed.

A time step range of $1e^{-5}$ to $1e^{-3}$ s is effected with 20 inner iterations in order to reduce the truncation error in numerical calculations. A solution convergence criterion of residual of $1e^{-6}$ for pressure and velocity and $1e^{-8}$ for heat transfer was fixed for validation. During the calculation, the cell zones either rotate or translate relative to one another along the mesh interface in discrete steps. Since the flow is inherently unsteady, the motions of moving zones are tracked relative to the stationary frame. Time step size

was selected based on the principle that the time step should be no larger than the time it takes for a moving cell to advance past a stationary point.

Results and discussions

The analysis and data extraction were confined to FBT and Propeller in Baffled and in Unbaffled vessels with scraper. The analysis was also done using Paddle impeller for Baffled vessel. It was performed at a speed of 150 rpm for FBT and Propeller in Baffled vessel. In Unbaffled vessel with scraper and with Paddle impeller, the speed rpm was set at 80 rpm for the three types of milk. The reason for the limited analysis is that, high $\bar{h}$ values were obtained experimentally at these rotational speeds. Finally, all these were performed to elicit information on velocity vector profiles, transient temperature profiles and $\bar{h}$ values with a view to theoretically verify and simulate the experimental results.

In the case of FBT for all three types of milk, these profiles show radial currents emanating from the tip of impeller blades. The flow currents divide with part of it moving down and being sucked into the eye of the impeller. The other part raises along the baffle and flow down from top. The values of velocity vectors, are indicated in the side scale. In the case of Propeller, predominantly vertical axial flow currents generated are observed in the profiles. The downward flowing vertical currents are drawn by the impeller and pitched down further. The strong flow currents move along the bottom surface to raise again along the baffle.

The magnitude of velocity vectors for Propeller show higher scalar values than FBT. This justifies higher convective heat transfer coefficient values for Propeller compared to FBT.

However, the magnitude of velocity vectors show decreasing trend from Cow milk to Standardised milk to Full cream milk. This is probably indicative of the influence of increasing fat content from Cow milk to Full cream milk in slowing down the flow currents. The reduction in flow currents results in lowering the $\bar{h}$ values.

Baffled vessel

A sample CFD analysis with FBT and Propeller at 150 rpm for the three types of milk in Baffled vessel is shown in Fig. 3.

The velocity profiles in the figure show intense axial flow currents for Propeller in comparison to radial flow currents emanating from the tip of the impeller and dividing partly upward and partly downward for FBT. The

scalar values of velocity for FBT are lower than that of Propeller. The scalar velocity values of 0.02–0.1 m/s for FBT are lower than that of Propeller at 0.02–0.18 m/s for cow milk Fig. 3a, b. For standardised milk they are 0.02–0.09 m/s for FBT and 0.02–0.14 m/s for Propeller Fig. 3c, d. In the case of Full cream milk the corresponding values are 0.02–0.08 m/s for FBT and 0.02–0.13 m/s for Propeller Fig. 3e, f. These values were derived at from the global colour intensity of milk region and the corresponding scalar values in the legend. These values clearly point out that the Propeller is able to provide higher intensity flow currents, which enhances convective heat transfer coefficient in comparison to FBT. Also it is observed that the magnitude of the flow currents decrease irrespective of the type of impeller from cow milk (3.5% fat) to standardised milk (4.5% fat) to full cream milk (6% fat) justifying the decreasing trend in $\bar{h}$ values due to increasing fat contents of milk in turn that increase the viscous resistance to velocity.

A sample CFD analysis with Paddle impeller at 80 rpm for the three types of milk in Baffled vessel is shown in Fig. 4. As mentioned in the earlier paper, the Paddle was designed with 0.8:1 ($D_a:D_i$) ratio. Because of this design, it was reasoned that in spite of low rotational speed, Paddle impeller provided the highest heat transfer coefficients for the three types of milk due to higher volumetric circulation rates of flow, which is confirmed by CFD analysis. The velocity profiles in the Fig. 4 show 0.12–0.31 m/s, 0.12–0.30 m/s and 0.12–0.25 m/s for cow milk (3.5% fat), standardised milk (4.5% fat) and full cream milk (6% fat) respectively, which exhibit the ability of Paddle impeller in providing the highest $\bar{h}$ values. The influence of increasing fat contents impeding the flow is also clear from the above data, which results in decreasing $\bar{h}$ values from cow milk to standardised milk to full cream milk.

Unbaffled vessel with scraping

The velocity profiles for Propeller and FBT impellers for cow, standardised and Full cream milk at 80 rpm are shown in Fig. 5 Here again it is observed that Propeller generates flow velocities in the range of 0.3 m/s, 0.25 m/s and 0.22 m/s for cow milk, standardised milk and full cream milk respectively. Whereas the corresponding values are close to 0.28 m/s, 0.23 m/s, and 0.2 m/s for FBT. Another observation is, there are no velocity vectors below the scraper. This shows that the scraper wipes the heating surface effectively, preventing any layer formation, which would otherwise reduce convective heat transfer. Accordingly the $\bar{h}$ values are also higher than those in Baffled vessel. The $\bar{h}$ values were reported in the earlier paper.

Fig. 3 Velocity profiles at 150 rpm in Baffled vessel
a FBT, **b** Propeller—Cow milk (3.5% fat), **c** FBT, **d** Propeller—Standardised milk (4.5% fat), **e** FBT, **f** Propeller—Full Cream milk (6% fat), cross section view, plan view at position of impellers

Fig. 4 Velocity profiles at 80 rpm Paddle impeller—
a Cow milk (3.5% fat),
b Standardised milk (4.5% fat),
c Full Cream milk (6% fat),
 cross section view, plan view at position of impellers

Fig. 5 Velocity profiles at 80 rpm in Unbaffled vessel with scraper **a** FBT, **(b)** Propeller—Cow milk (3.5% fat), **c** FBT, **d** Propeller—Standardised milk (4.5% fat), **e** FBT, **f** Propeller—Full Cream milk (6% fat), cross section view, plan view at position of impellers

Table 1 Heat transfer coefficient ($\bar{h}$) data (A) in Baffled vessel (B) in Unbaffled vessel with scraper—Experimental (Exptl) vs CFD

Types of vessel	Types of impeller	n (rpm)	Cow milk (3.5%)			Standardised milk (4.5%)			Full cream milk (6%)		
			$\bar{h}$ Exptl ($\frac{W}{m^2K}$)	$\bar{h}$ CFD ($\frac{W}{m^2K}$)	Error (%)	$\bar{h}$ Exptl ($\frac{W}{m^2K}$)	$\bar{h}$ CFD ($\frac{W}{m^2K}$)	Error (%)	$\bar{h}$ Exptl ($\frac{W}{m^2K}$)	$\bar{h}$ CFD ($\frac{W}{m^2K}$)	Error (%)
Baffled vessel	FBT	150	680	674	0.88	615	610	0.81	560	565	– 0.89
	Propeller	150	701	693	1.14	679	674	0.73	674	669	0.74
	Paddle	80	764	758	0.78	742	739	0.40	679	676	0.44
Unbaffled vessel	FBT	80	777	769	1.02	772	768	0.51	772	771	0.12
	Propeller	80	933	925	0.85	771	774	0.38	773	774	– 0.12

Heat transfer coefficient

The experimental $\bar{h}$ values were determined based on time-temperature data of the milk and transient energy balance model as explained in the earlier paper (Rajasekaran et al. 2018). Theoretical values using CFD is compared with experimental data as presented in Table. 1. It can be seen that CFD data are in close agreement with the experimental $\bar{h}$ values within ($\pm 1\%$) error.

Conclusion

- CFD simulation for three types of milk has been carried out at 150 rpm for FBT and Propeller and at 80 rpm for Paddle in Baffled vessel. In Unbaffled vessel with scraper, the speeds of FBT and Propeller were set at 80.
- The velocity profiles and their magnitude generated have helped in reinforcing the reason for relative performances of the impellers observed during the experimental investigation as well as the influence of fat contents in the milk.
- The heat transfer coefficient values ($\bar{h}$) computed by ANSYS Fluent software exhibits a close agreement with the experimental data.
- This would serve as a basis for in depth CFD analysis thermal processing of milk and other fluids during agitation.

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