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Internal energy analysis with nanofluids in header and riser tube of flat plate solar collector by CFD modelling

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Abstract. In this study, Computational Fluid Dynamics (CFD) modelling of internal energy with different nanofluids (TiO_2 and crystal nano cellulose) studied. The modelling was three dimensional under Viscous Laminar model. The base fluid for nanoparticles was 60% water+40% ethylene glycol along with individual water and ethylene glycol fluids. Volume fraction of nanofluids was 0.5% and single-phase model used. The diameter of inlet and outlet was fixed of individual model and three kinds of designing model used here. The diameter of both header and riser tubes varied whereas the number of tubes varied only for riser. The results revealed that diameter and number of tubes (riser) do not affect on the internal energy. Since internal energy only depends on different properties of the inside fluids.

1. Introduction

Solar energy is the most promising renewable energy due to its extensibility and abundant in nature. Negative impact and depletion of fossil fuels enslaved forcefully to realize alternative sources of energy [1, 2]. Green technology revolution has been trying to minimize these burning issues by implementing renewable energies in place of fossil energies. Academic and industrial enterprises participated to build the strongest foundation of renewable energies as well. As consequences, computational numerical simulation has been exposed as a vital tool for improving the industrial process performance and process optimization [3] such as Computational Fluid Dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer and associated phenomena with chemical reactions [4]. By creating virtual design in CFD and the simulation of design should be done easily without practical design model [5].

Many engineering problems [6] as well as various numerical simulations have been performed on solar energy in order to replace the fossil energy successfully [7]. In solar collector, working fluid is flowing through header and riser tubes and the tubes are fixed together in harp-shaped. Generally, water and oil used as working fluids [8]; meanwhile this working fluids has already been changed by several number of researchers to improve the performance of solar collector [9, 10]. Moreover considerable numbers of journals have been published on CFD simulations in case of flat plate solar collectors [11]. Gunjo, Mahanta and Robi [12] validated experimental values of outlet water and absorber plate temperature with numerical values using CFD software of a solar flat plate collector with straight riser and header arrangement. Different operating parameters such as solar insolation, ambient temperature, inlet water temperature and mass flow rate used and found developed model could predict outlet water and absorber plate temperature of heating system with reasonable accuracy. Selmi, Al-Khawaja and Marafia [13] studied the problem of water flow in flat plate solar collector simulating with CFD software. CFD modelling has been done of solar irradiation and the modes of mixed convection and radiation heat transfer. They revealed a good agreement between experimental and simulated results. Notwithstanding the novelty of nanoparticles is unparalleled, it also create some negative impact on to the environment as nano toxicity. Nano toxicity is a catastrophic substance and can deface human being and plants [14-17]. As consequences recently the researchers are concentrating more on biodegradable and eco-friendly nanoparticles. Therefore, crystal nanocellulose attracts more attention due to its biodegradability, plentiful in nature, clear, lower density good, mechanical properties and especially green attributes to the environment [18-20].

The purpose of this research is to investigate the effect of diameter and number of tubes (riser) on internal energy with different fluids (water, TiO$_2$, ethylene glycol, 60% water+40% ethylene glycol, crystal nanocellulose) flowing through inside the tubes with constant temperature boundary condition. As different researchers used individual dimension of header and riser tube in experiment and numerical analysis study, therefore to select a distinct dimension is very ambitious. Here three types of design models are prepared with various diameters and numbers of riser tubes using "SOLIDWORKS" software for CFD simulations. The ANSYS workbench with Fluent Flow software used for this numerical simulation and the model was Viscous Laminar.

2. Nanofluids Physical Properties

Density of nanofluid defined as [21],

$$\rho_{nf} = \varphi \rho_p + (1-\varphi)\rho_f \tag{1}$$

Thermal equilibrium define the specific heat of nanofluids [22] as Eq. 2,

$$c_{p,nf} = \frac{\varphi(\rho c_p)_p + (1-\varphi)(\rho c_p)_f}{\rho_{nf}} \tag{2}$$

Thermal conductivity of nanofluids [23] calculated by the following equation,

$$\frac{k_{nf}}{k_{nf}} = \frac{k_p + 2k + 2\varphi(k_p - k_{bf})}{k_p + 2k - \varphi(k_p - k)} \tag{3}$$

According to literature review, Einstein model of viscosity determine increasing nanoparticles volume concentration linearly increases the viscosity of the suspension [24],

$$\mu_{nf} = (1 + 2.5\varphi)\mu_{bf} \tag{4}$$

Calculative values of density, specific heat, thermal conductivity and viscosity of different nanofluids have been executed using the above equations (1 to 4). Table 1 illustrates the calculative physical properties of different fluids and nanofluids. Reynolds number and flow behaviour has been identified empirically by the (Eq.(5)) Reynolds [25];

$$\mathrm{Re} = \frac{\rho D v}{\mu} \tag{5}$$

Table 1. Physical properties of required fluids and nanofluids

Physical properties	Water	Ethylene Glycol	60% Water+40% EG	TiO_2	Crystal nano cellulose
Density (kg/m^3)	998.2	1111.4	1050	2640	1050
Specific heat (j/kg.k)	4182	2415	3600.648	1270.424	2450.324
Thermal conductivity (W/m.k)	0.6	0.252	0.260	0.91	0.31
Viscosity (kg/m.s)	0.001003	0.0157	0.0022	0.00495	0.00495

3. CFD governing equations

For the computational simulations of required flow geometries and boundary conditions; CFD approach usages the numerical calculation to solve the governing equations. In this study the flow pattern with constant temperature through a combined structure of two circular tubes are simulated using the FLUENT software ANSYS R15.0. Here only single-phase model is set for simulations and simulations done in steady state conditions by solving mass, momentum and energy conservation equations as [26],

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{6}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho U) + \nabla \cdot (\rho U U) = -\nabla P + \nabla \tau + \rho g \tag{7}$$

Energy Equation:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho U c_p T) = \nabla \cdot (k \nabla T) \tag{8}$$

4. Methodology

4.1 Designing of Geometry

The models are designed and developed in Solidworks (version 2016). The diameters and of header and riser tube are varied in this study. Table 2 illustrates the parameters of header and riser tube of solar collector. In addition, the number of header tubes is fixed but it varied for riser tubes. Minitab software used to make design statistical approach of geometries showed in Table 3. Three dimensional geometry of header and riser tube is generated here. Figure 1 shows the general view of combined header and riser tube of flat plate solar collector. All models have equal number (two) of header tubes but number of riser tubes varied such as eight, twelve and sixteen accordingly.

4.2 Modelling Procedure

The geometries have been imported to design modeler in ANSYS R15.0 for computational simulation. Automatically Tetrahedrons and CutCell meshing has been done in the three-dimensional computational domain. Figure 2 exhibits 3D meshed model of header and riser tube. Table 4 presents the common mesh sizing parameters for all models. In addition, mesh independence test studied by changing mesh sizing Relevance Center such as coarse, medium and fine. Pressure-based, Absolute-velocity and Time-steady solver used in this study. Energy equation and Viscous-Laminar model used [27, 28]. In case of Boundary Condition, mass flow rate 0.0083 kg/s and temperature 307k was fixed [29, 30].

Table 2. Parameters of header and riser tubes for three-dimensional modelling.

Parameters	Dimension	
	Header tube	Riser tube
Diameter (mm)	22, 23 and 24	10, 11and 12
Thickness (mm)	0.6	0.45
Length (mm)	1000	1714
Number of tubes	2	8, 12 and 16

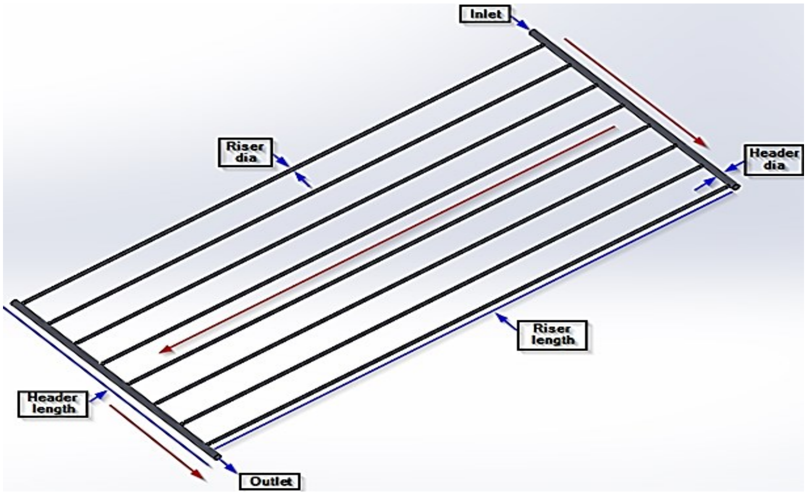
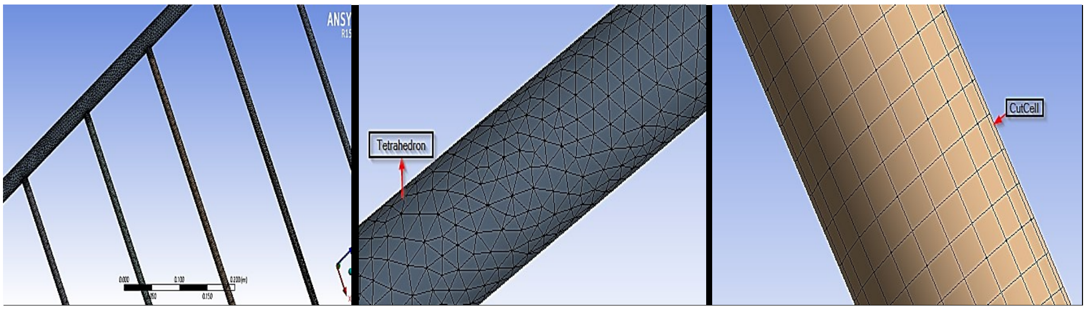


Figure 1. Schematic view of basic design model of header and riser tubes



(a) (b) (c)

Figure 2. Meshing (a) 3D model, (b) Tetrahedron meshing (c) CutCell meshing.

Table 3. Statistical presentation of designing for geometry.

Number of Riser Tube	Header Diameter (mm)	Riser Diameter (mm)
8	23	10

12	22	12
8	24	11
16	24	11
16	22	11
12	23	11
16	23	10
12	22	10
12	24	12
16	23	12
8	22	11
12	24	10
8	23	12

Table 4. Parameters of Mesh Sizing.

Sizing	Setting
Advance Size Function	Curvature
Relevance Centre	Coarse
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Slow
Span Angle Center	Fine
Curvature Normal Angle	Default (18.0^0)
Growth Rate	Default (1.20)

Solution calculation is performed based on Pressure-velocity coupling with Simple Scheme and Spatial Discretization. The Solution Control parameters (Under-Relaxation Factors) for the computational simulation are presented in Table 5. Figure 3 presents the converged solution of the simulation and it is relatively similar for all of models.

Table 5. Solution Control Parameters.

Parameters	Setting Values
Pressure	0.3
Density	1
Body Forces	1
Momentum	0.7
Energy	1

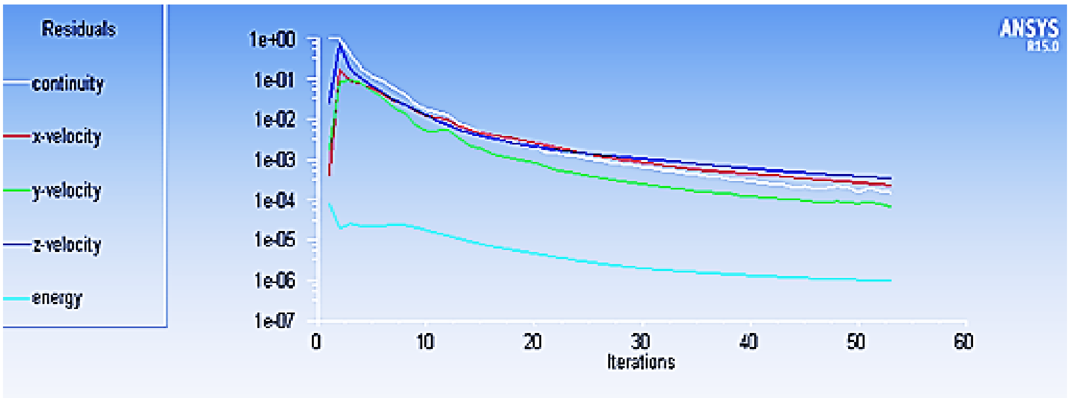
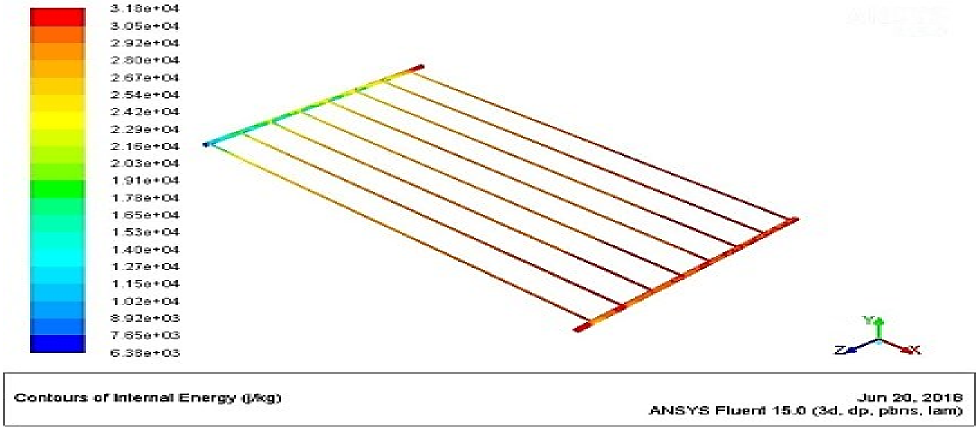


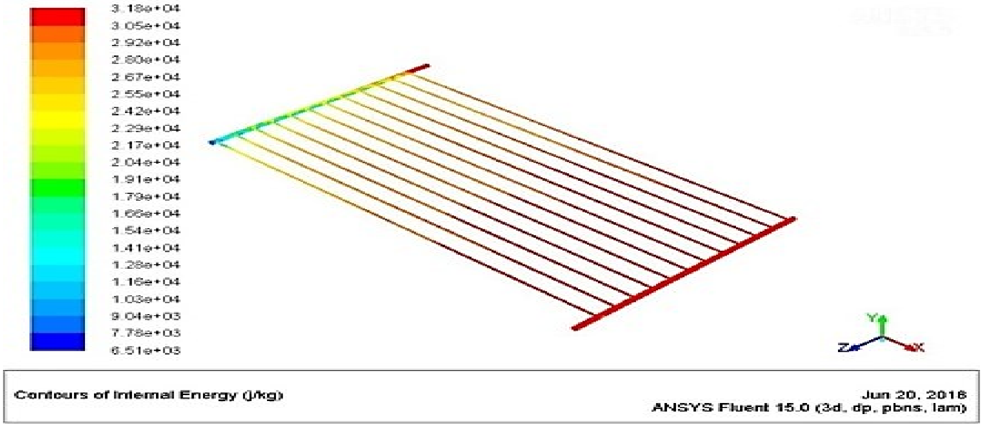
Figure 3. Converge solution

5. Result and Discussion

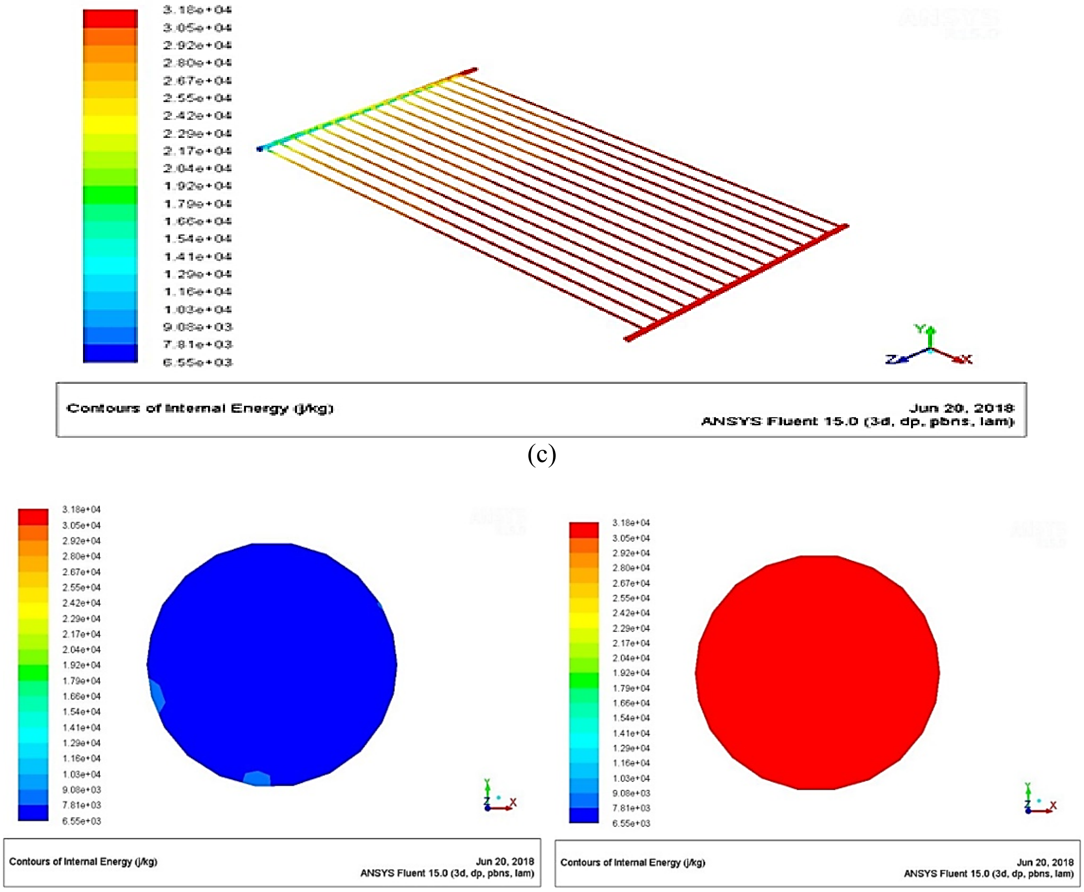
The results of computational simulations can be analysed in numerical data as in Table 6 or graphical view as in Figure 4. Numerical values of internal energy represent that diameter and number of tubes has no effect on it. All designs show some differences in minimum values of internal energy whereas maximum values are unchanged. Although mesh or grid independence test has been conducted but the results are consistent for all designs. Therefore, internal energy of header and riser tubes depends on the internal fluid characteristics rather than diameter and the number of tubes. Different fluid exhibits individual energy range according to their properties as shown in Table 6. Besides, outlet (Figure 4e) showed fully development of solution. However, some designs are not compatible with all kinds of fluid flow as Figure 5 represents the interrupted trend of energy equation.



(a)



(b)



(c)

(d) (e)

Figure 4. Contours of internal energy (a) model X, (b) model Y, (c) model Z, (d) inlet and (e) outlet.

Table 6. Numerical values of internal energy of fluids and nanofluids.

Design	Parameters	Internal Energy	
		Min(j/kg)	Max(j/kg)
8-22-11	Water	7555.765	36909.2
	Ethylene Glycol	4359.228	21281.57
	60%Water+40%Ethylene Glycol	N/A	N/A
	TiO_2	2288.478	11204.88
	Crystal nanocellulose	4414.128	21588.86
8-23-10	Water	7519.131	36909.19
	Ethylene Glycol	4343.408	21281.56
	60%Water+40%Ethylene Glycol	N/A	N/A
	TiO_2	2288.026	11204.88
	Crystal nanocellulose	4375.026	21588.86
8-23-12	Water	7602.524	36909.1
	Ethylene Glycol	4365.053	21281.57
	60%Water+40%Ethylene Glycol	6543.348	31769.23
	TiO_2	2311.612	11204.88
	Crystal nanocellulose	4421.486	21588.86
8-24-11	Water	7328.505	36909.19

	Ethylene Glycol	4286.926	21281.54
	60%Water+40%Ethylene Glycol	6381.715	31769.23
	TiO_2	2242.375	11204.38
	Crystal nanocellulose	4316.959	21588.84
12-22-10	Water	7582.486	36909.2
	Ethylene Glycol	4353.318	12181.58
	60%Water+40%Ethylene Glycol	6537.199	31769.24
	TiO_2	2310.3	11204.38
	Crystal nanocellulose	4388.4	21588.87
12-22-12	Water	7584.952	36909.21
	Ethylene Glycol	4376.075	21281.57
	60%Water+40%Ethylene Glycol	6560.45	31769.24
	TiO_2	2311.537	11204.88
	Crystal nanocellulose	4436.216	21588.87
12-23-11	Water	7496.358	36909.2
	Ethylene Glycol	4342.002	21281.58
	60%Water+40%Ethylene Glycol	6493.067	31769.24
	TiO_2	2259.208	11204.88
	Crystal nanocellulose	4369.304	21588.87
12-24-10	Water	7496.358	36909.2
	Ethylene Glycol	4342.002	21281.58
	60%Water+40%Ethylene Glycol	6513.174	31769.24
	TiO_2	2261.074	11204.88
	Crystal nanocellulose	4369.304	21588.87
12-24-12	Water	7615.049	36909.2
	Ethylene Glycol	4374.993	21281.58
	60%Water+40%Ethylene Glycol	6546.11	31769.24
	TiO_2	2311.431	11204.88
	Crystal nanocellulose	4434.519	21588.87
16-22-11	Water	7601	36909.2
	Ethylene Glycol	4364.763	21281.57
	60%Water+40%Ethylene Glycol	6542.221	31769.24
	TiO_2	2311.612	11204.88
	Crystal nanocellulose	4426.937	21588.87
16-23-10	Water	N/A	N/A
	Ethylene Glycol	N/A	N/A
	60%Water+40%Ethylene Glycol	6413.789	31769.23
	TiO_2	2311.472	11204.23
	Crystal nanocellulose	4433.686	21588.87
16-23-12	Water	7375.112	36909.2
	Ethylene Glycol	N/A	N/A
	60%Water+40%Ethylene Glycol	6303.268	31769.24
	TiO_2	2306.632	11204.88
	Crystal nanocellulose	3740.407	21588.86
16-24-11	Water	7600.43	36909.2
	Ethylene Glycol	4370.075	21281.72
	60%Water+40%Ethylene Glycol	6553.69	31769.23
	TiO_2	2311.864	11204.88
	Crystal nanocellulose	4426.148	21588.87

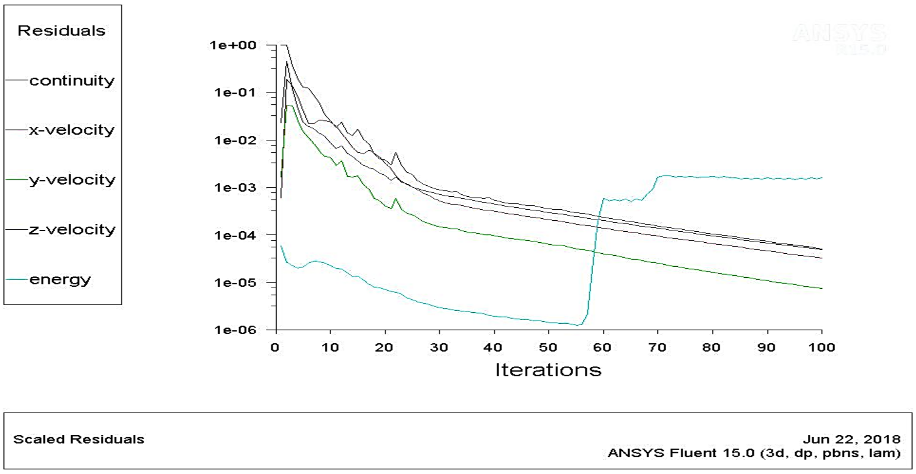


Figure 5. Discontinuation of energy equation converge solution.

6. Conclusion

In this numerical simulation, the effect of number and diameter of tubes (header and riser), on internal energy with different fluids flowing through the tubes has been studied using ANSYS R15.0. The simulation results showed that diameter and number of tubes of flat plate solar collector do not affect on the internal energy significantly. Internal energy primarily depends on the physical properties of inside fluids. Besides, some designs are not convenient with some fluids flowing through inside the design model.

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