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CFD based study of thermal performance of shell and tube heat exchanger with discharging PCM

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Abstract: Heat transfer from one fluid to another is important application in engineering science, various type of heat exchanger devices was developed by engineers from previous decades. Research on these devices continues in present era to improve thermal performance. Simple shell and tube heat exchanger was use to validate the experimental results with CFD results. Experimental validation proves that CFD is effective tool for thermal performance investigation. After experimental validation, main research work was focused on effect of latent heat on thermal performance improvement of simple shell and tube heat exchanger using PCM materials with these being discharging in it

Keywords: Thermal performance, CFD and Phase change material (PCM)

1. Introduction

In present era heat, storage from thermal devices is main research focus for engineers, designers, and researchers worldwide. Various new techniques was developed like extended surfaces, phase change material, latent heat storage devices, thermo electric devices and many more. Present research work will focus PCM application in shell and tube heat exchanger for discharging boundary conditions. Various experimental and CFD based research work was summarized for this research work. Heat exchangers have various applications in power plants, refrigeration and air conditioning systems, nuclear reactors, automotive industries, chemical processing, heat recovery systems, and food industries.

Thermal energy includes storage of heat in one of three forms;

- Sensible Heat storage.
- Latent heat storage.
- Thermo-chemical heat storage.

Sensible heat energy storage

It is very common method and used from hundreds of years as hot water tank as water consumes large without changing its phase. Sensible heat storage simply means changing the temperature of storage medium. Most commonly storage medium is water but rock, sand, clay and earth can also be used.

Latent heat energy storage

It includes the storage of energy in Phase-change materials (PCM`s). Phase change material are those material which changes their phases by consuming heat energy into them. Thermal energy is stored and released with change in the materials phase. Most common phase change to exploit is solid -liquid transition, as the liquid–gas transition is impractical and solid-solid (crystalline structure) transition usually have too low an energy density to be useful. When a PCM is heated initially it behave like sensible heat energy storage and the material temperature is increased. However, once their transition temperature is reached the material will continue to absorb heat a constant temperature while it changes state or phase. This heat absorbed at constant temperature is known as the latent heat of the transition. To retrieve the energy the PCM can be changed back from the liquid to the solid phase and the energy stored as latent heat is released.

Thermo chemical heat energy storage

It includes storing heat energy in the form of chemical bonds. A reversible chemical reaction which absorbs heat is used to absorb the heat energy that is to be stored. This reaction can be reversed to release the stored heat. The most common reaction used for this process is the hydration of salts.

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2. Objective of Present Research Work

Present research work will focus on thermal performance analysis of phase change material (PCM) application on shell and tube heat exchanger for discharging boundary conditions. All cases will be developed using design of experiment (DOE) technique named "taguchi method" total four factors and levels will be selected for this case study. Experimental validation will also performed for this study for same shell and tube heat exchanger for water base fluid. PCM based results will target by CFD software Ansys fluent software. Model equation generation will also performed for this research work suing ANOVA analysis

3. Literature Review on Phase Change Material (Pcm) and Its Applications

An Experimental and numerical study has been done by**(Agarwal & Sarviya, 2016)** to develop the latent heat storage for solar dryer and calculate its performance during charging and discharging. Stored energy in the latent heat storage is utilized during non-sunshine hours to heat ambient air by forcing the ambient air through the latent heat storage system study also indicate that heat transfer during charging is largely influenced by natural convection process.Melting of PCM first occurred at the uppermost sectionof the system, and then it moves downward and results show that melting rate is faster at theuppermost section due to buoyant effect, further studies show that by decreasing the temperatureof HTF from 90 °C to 80 °C, the charging time is increasedby 20%. Heat transfer during discharging is mainly governed by conductionand due to low thermal conductivity of PCM, the rate of heattransfer during discharging is comparatively low. Time required for discharging of LHS is longer compared to timerequired for charging of LHS due to lowheat transfer rate betweenPCM and HTF during discharging. The discharging time increased by 23% by decreasing the HTFflow rate from 0.003 kg/sec to 0.0015 kg/sec

(Wang, Lin, Li, & Zheng, 2016) experimentally investigation have made to study the effects of temperature change on thermal storage performance of the phase change material paraffin with and without copper foam as a filler material. Study analyzes the relationship between the complete phase transition time and heat source temperature of paraffin and of composite PCM. It simulates the phase change process of paraffin and composite phase change material using CFD software Fluent. Results show that Copper foam can effectively improve the uniformity of paraffin'sinternal heat transfer while reducing the heat storagetime by more than 40%, also increasing temperature can improve thermal storage efficiency.Comparison of experimental and simulation results showthat: the phase transformation process of metal foam andparaffin can be effectively simulated by software melting/solidificationand porous media model under a certain condition.
(Englmair et al., 2016)have experimentally investigated on data from initial testing of heat storage modules, containing different mixtures of the PCM sodium acetate trihydrate, are presented. Modules in different material configurations have previously been tested under laboratory conditions to prove the concept. The modules form a long-term heat storage as a part of a solar combisystem including additionally a solar collector field and a water buffer storage. The solar combi-system was connected to an automated tapping system simulating domestic hot water tapping and space heating demands.In results Stablesupercooling was achieved in three out of four modules after they were charged with solar collectors as a fluctuating heat source.

(Eslamnezhad & Rahimi, 2017)experimentally studies have done on enhancement on heat transfer method using rectangular fin to melt the PCM in a triplex tube heat exchanger has been investigated numerically to increase the efficiency of the heat exchanger and to reduce the time of PCM melting by changes done in the structure of the fins inside of the triplex tubes when the fin contacting surface with the PCM has kept constant. According to obtained results the impact of fin location on melting of the PCM is very important in triplex type heat exchangers in which the gravity and natural convection play important role in PCM melting.

(Pointner, Steinmann, & Eck, 2014)introduces the PCM Flux approach (PCM Flux consists of macro encapsulated Phase change material blocks that are arranged as parallel layers)as a new alternative for latent heat energy storage. The storage material is separated mechanically by an intermediate fluid layer from the heat transfer surfaces. This concept avoids the formation of a growing layer of solidified PCM material covering the heat transfer structure, which limits the heat flux. PCM storage systems mainly have a disadvantage while it gets discharging. The heating power decreases over time due to a growing and isolating layer of solidified PCM on the heat exchanger. Systems with locally fixed storage material, all of which show this behavior, are stationaryPCM.MovingPCMbycontrast, make use of locally unfixed PCM offering the possibility to remove the isolating layer of solidified PCM. Thus, a constant thermal power over a span of time is possible. PCM Flux is considered to be a very promising concept, eliminating the problem of decreasing heating power with time.

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(Johansen et al., 2016)experimentally studies have done on a solar combi system with a heat of fusion storage based on the phase change material (PCM) sodium acetate trihydrate (SAT). SAT is a salt hydrate with several qualities which make it suitable for heat storage in one family houses. When SAT has been heated to a certain high temperature, above 80 °C, it is possible for the SAT to supercool below its melting point of 58 °C to ambient temperature. In this phase it still contains latent heat and can stay in this state for many months. When there is a heat required a seed, crystal is introduced to the supercooled SAT and in a matter of minutes the whole volume get solidifies releasing its latent heat. To only release an amount of heat suitable to the requirement it is necessary to divide the SAT volume into separate volumes.

(Dermardiros, Chen, & Athienitis, 2015)presents results of an experimental and numerical study focusing on the control based modelling of an activelycharged/discharged phase-change material (PCM) thermal energy storage (TES) system. The PCM-TES system consists of fivelayers of commercial macro-encapsulated PCM panels with an air holes in its center. Air can flow through this cavity tocharge/discharge the PCM panels. A detailed fifth order thermal network finite difference model for the system is developed and verified againstexperimental results. The detailed model is then simplified to a 2nd order model for control purposes. A five-parameter equation isdeveloped to model of the storage of heat in the PCM. An average and maximum temperature difference of 0.8°C and 2.0°C,respectively, is achieved between the experiment data and that simulated by the detailed model. The second order model has anaverage and maximum temperature difference of 0.2°C and 0.9°C, respectively, compared to the detailed model. After literature review, it was concluded that in most of the research, papers limited CFD simulation work was performed and detailed research work was not available for CFD based simulation work.

4. The Conservation of Energy Equation for the Surface Heat Convection

$$Q_{convection} = hA\Delta T$$

$$Q_{convection} = hA(T_{wall} - T_{inside})$$

Here, h is convection heat transfer coefficient, A is perimeter of inner surface ($A = \pi DL$), T_{wall} is wall temperature of tube

Here, we consider that the inner surface temperature of a tube is constant. From energy balance equation

$$Q_{flow} = Q_{convection}$$

$$\dot{m}c_p\Delta T = hA\Delta T$$

$$h = \dot{m}c_p\Delta T / A\Delta T$$

Equation used for Reynolds number

$$Re = \frac{4\dot{m}}{\pi D\mu}$$

Equation used for Nusselt number

$$Nu = \frac{hD}{K}$$

Here, D is hydraulic diameter or inner diameter

Correlation equation for Nu number given by Dittus-Boeltler

$Nu = 0.02Re^{0.8}Pr^{0.3}$,wherePr is prantl Number

Correlation equation for Nu number given by Gnielinski

$$Nu = \frac{\left(f/_8\right)(Re - 1000)Pr}{1 + 12.7\left(f/_8\right)^{0.5}(Pr^{0.67} - 1)}$$

Where f is friction factor and formula for f is given by Petukhov

$$f = (0.79\ln(Re) - 1.64)^{-2}$$

5. CFD Modelling

Computational fluid dynamics (CFD) is the branch of fluid dynamics. It is a research tool which provides cost effective means,simulate real flows by use of the numerical solution of governing equation. Main governing equation is Navier-storke equation for Newtonian fluid. Computational technique used algebraic equation in the place of governing partial differential equation and solve by digital computer. It also provides testing condition which are not possible to measure experimentally and cannot solve by analytics solutions.

Steps of CFD process:

- Mathematical modeling (partial differential technique)

- Numerical method (Discretization and solution technique)
- Software tool (solver, pre-andpost processing)

CFD STEPS

Here we are used Ansys 14.5 version. In Ansys, fluent software is used as solver for analysis of fluid flow and geometries are seen in fig. 1 to fig. 4. We are used CFD steps for solving problem.These steps are:
Step1: - CAD-file making (geometry): -In this step we are creating design of given problem by used of Ansys design modular and another designing tool like catia, inventor, AutoCAD, Pro-e etc.

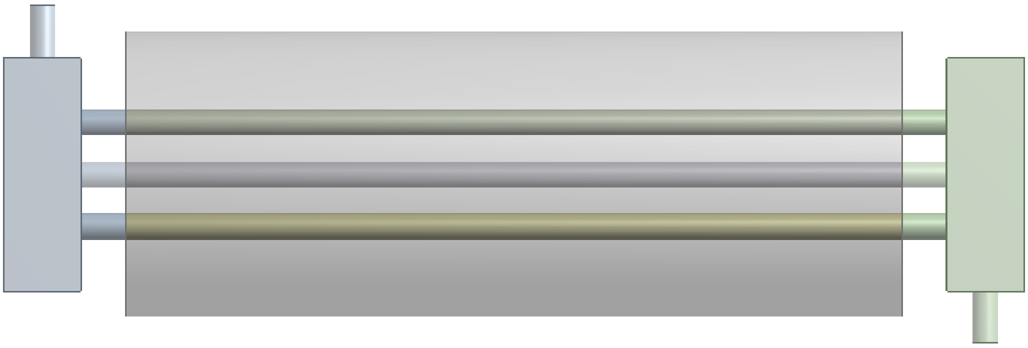

Fig. 1: Design Shell and Tube Heat Exchanger (CFD)

Step 2: -Discretization (meshing): -After designing of geometry off given fluid or component it is braked in to very small or discrete cell (Mesh Generation) by ICEM CFD. Here tube is uniform or block is non-uniform structure.

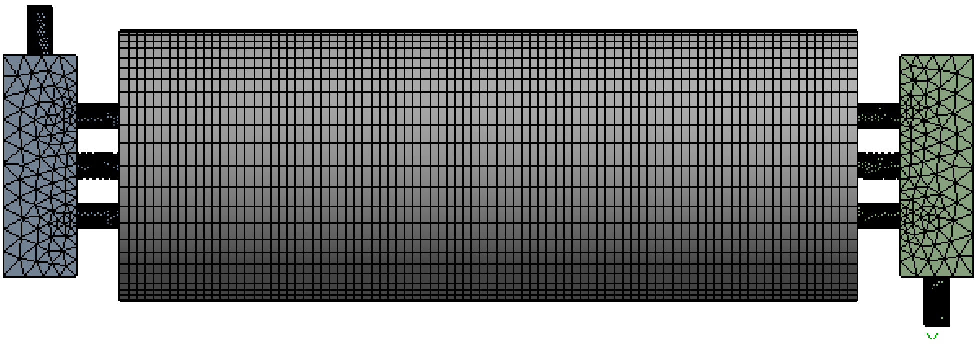

Fig. 2: Discretization of Heat ExchangerDesign 1

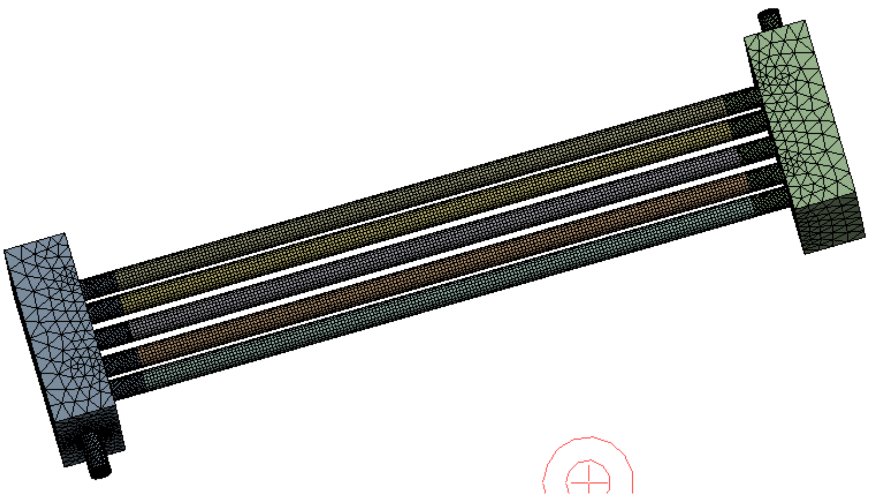

Fig. 3: Meshing of domain

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Step 3: - Boundary name: -After meshing we give name of boundary.

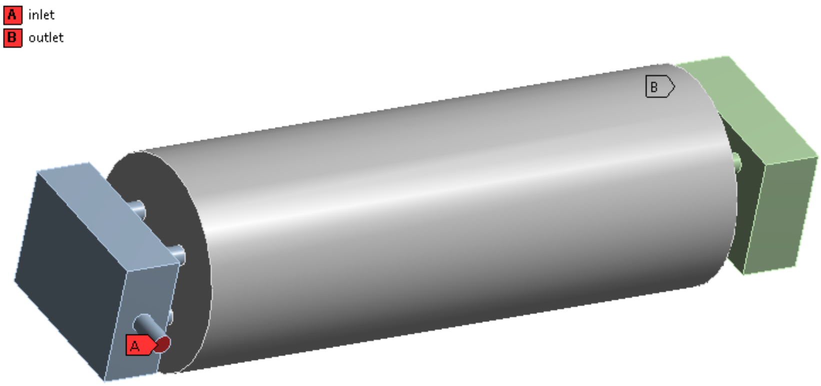

Fig. 4: CFD Boundary conditions for Heat Exchanger

Step 4:- Solver setting (setup): - After giving name of boundary, fluent software is used as solver. It is used default under relaxation factors to start a calculation. Under relaxation is includes to stabilize the iterative process for the pressure based solver.

Discretization Scheme

Variable	**Scheme**
Pressure	Standard
Momentum	Second Order Upwind
Turbulent Kinetic Energy	First Order Upwind
Turbulent Dissipation Rate	First Order Upwind
Energy	Second Order Upwind

Step 5: - Run solution (solution):-Fluent reports value of residuals, which are indications of the error in the current solution. These should decrease during the calculation. There is guideline on the reductions that indicated a solution is “converged”.

6. Results and Discussions

The present chapter gives the application of the Taguchi experimental design method. The scheme of carrying out experiments (Simulation work) was selected and results are presented in fig. 5 to fig. 7 and Table 1 and Table 2.

Table 1: Factor and Level for PCM-HE

No	**Factor**	**Level I**	**Level II**	**Level III**	**Level IV**
1	Mass flow rate(MFR) (kg/sec)	0.1	0.2	0.3	0.4
2	Temperature (In Temp) (K)	320	330	340	350
3	PCM-Type	1	2	3	4
4	HE-Design	1	2	3	4

PCM type represent different type of PCM material available in local market. HE-Design represent internal design of shell of heat exchanger, which should effect on efficiency of heat exchanger.

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Table 2 L16 Orthogonal Array for Present research work for discharging of PCM

No.	MFR	In_Temp	PCM	Design	Discharging
1	0.1	320	1	1	40.00
2	0.1	330	2	2	26.00
3	0.1	340	3	3	28.00
4	0.1	350	4	4	43.00
5	0.2	320	2	3	23.00
6	0.2	330	1	4	32.00
7	0.2	340	4	1	41.00
8	0.2	350	3	2	32.00
9	0.3	320	3	4	28.00
10	0.3	330	4	3	21.00
11	0.3	340	1	2	35.00
12	0.3	350	2	1	30.00
13	0.4	320	4	2	38.00
14	0.4	330	3	1	31.00
15	0.4	340	2	4	29.00
16	0.4	350	1	3	34.00

Fig. 5: S/N ratio analysis for discharging of PCM

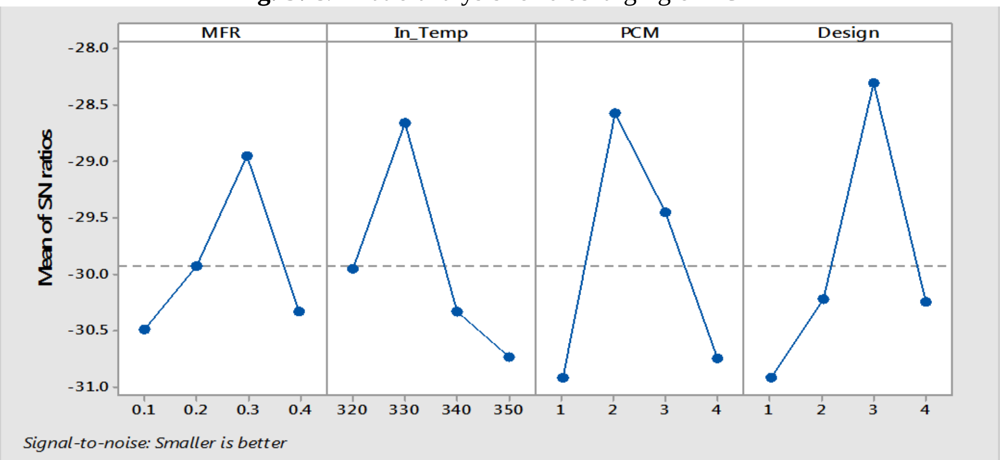

Fig. 6: Mean analysis for discharging of PCM

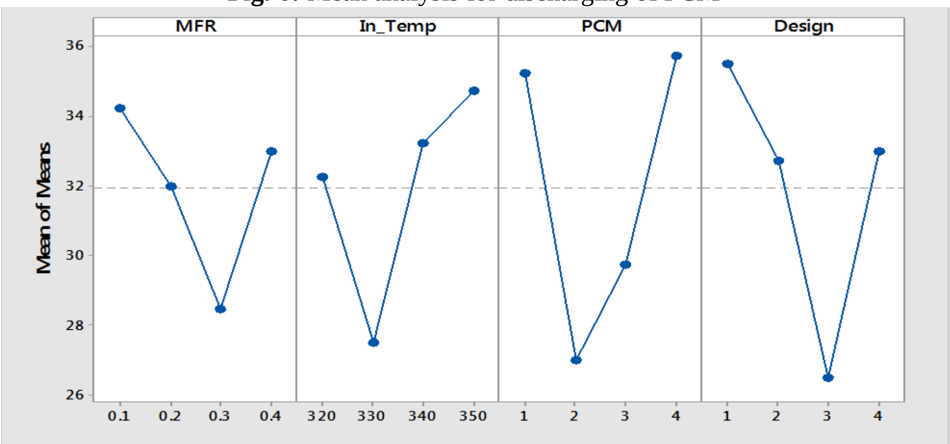

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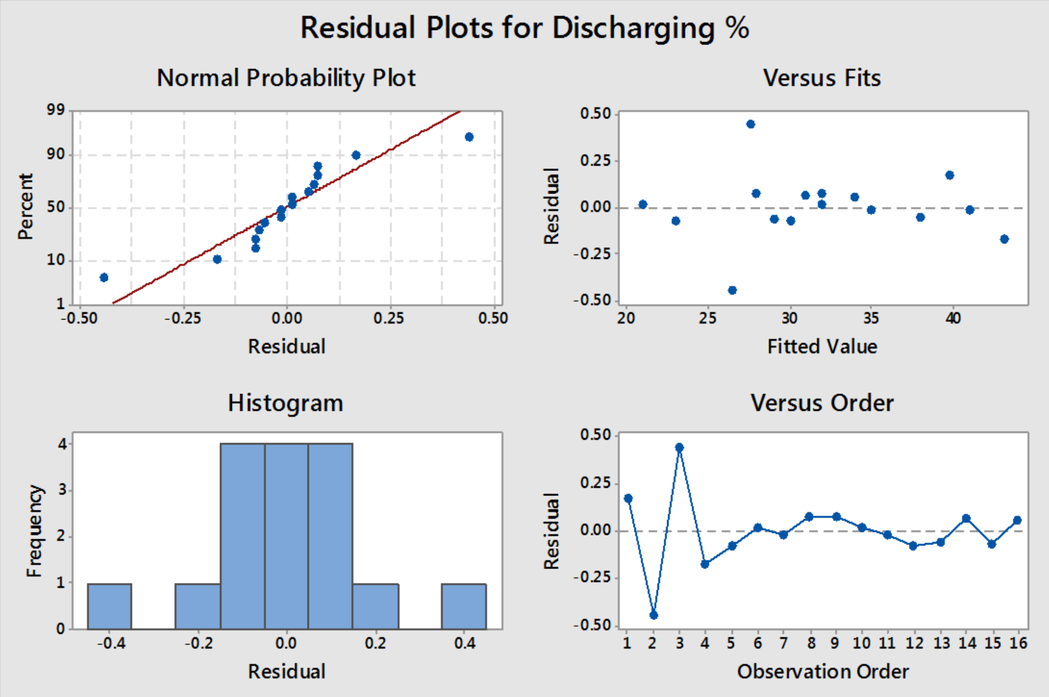
Fig. 7: Residual plots for discharging ANOVA analysis



Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0.494599	99.92%	99.39%	48.4273	91.91

Regression Equation

Discharging % = 1396 + 1346 MFR - 9.045 In_Temp - 362.4 PCM + 338.4 Design + 1169 MFR*MFR + 0.01563 In_Temp*In_Temp + 8.562 PCM*PCM - 2.500 Design*Design - 5.555 MFR*In_Temp - 26.22 MFR*PCM + 22.33 MFR*Design + 0.962 In_Temp*PCM - 1.000 In_Temp*Design

7. Conclusion

Present research work is complete for PCM role in heat transfer analysis used in shell and tube heat exchanger. Design of experiment technique Taguchi is used for present research work and analysis of variance is also performed for model equation generation. Table 3 represent the best case for parameter which affect the thermal performance mostly.

Table 3: Rank of factors using S/N ratio analysis for discharging

Level	MFR	In_Temp	PCM	Design
1	-30.39	-29.95	-30.91	-30.92
2	-29.92	-28.67	-28.58	-30.22
3	-28.95	-30.33	-29.45	-28.31
4	-30.33	-30.74	-30.74	-30.24
Delta	1.54	2.07	2.33	2.60
Rank	**4**	**3**	**2**	**1**

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