CFD ANALYSIS OF VARIABLE-TEMPERATURE CRYOGENIC COLD STORAGE DEDICATED FOR LIQUID AIR ENERGY STORAGE APPLICATIONS

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ABSTRACT

The growing share of weather-dependent renewable energy sources in national power systems carries the risk of system imbalance. One of the tools to support the system operator in ensuring stable energy supplies to consumers are energy storage facilities. One of the technologies for energy storage on a system scale is the LAES technology, based on the storage of liquefied air. The efficiency of energy storage in such an installation depends largely on the cold storage system.

The aim of the research is to analyze the cooperation of the LAES system with variable temperature cold store. The study covers CFD analysis of the cryogenic store using various materials. The analyzed store is dedicated for the LAES application, so fulfill its requirements in the field of temperature range and other physic-chemical properties. The study includes material selection, store geometry development, initial and boundary conditions determination. Mathematical model of the processes occurring in the packed-bed cold store was built and implemented to the dedicated numerical environment. Two material types were analyzed: PCM (phase change materials) and high heat capacity solid. Obtained results will be further used for assessment of variable operating conditions of the LAES system cooperating with a cryogenic variable temperature store.

1 INTRODUCTION

Actual changes in electricity generation structure forces new technologies development. Efforts aimed at carbon dioxide emissions reductions focus energy generation in the renewables sector. The main challenges operators need to face are unpredictability and uncontrollability of those sources, which could cause significant imbalances in system operation and quality problems while cooperating with huge conventional plants i.e. fossil fuel or nuclear power plants (Arraño-Vargas et al., 2022)(Hansen et al., 2019)(Kumar et al., 2020)(Basit et al., 2020).

One of the solutions, which may help to overcome these problems are system scale electricity stores. There are various technologies dedicated for electrical energy storage, but taking into account system scale demands (power, capacity, charging, discharging and storing time, costs) just several are suitable for such application: pumped hydro (PH), Compressed Air Energy Storage (CAES), hydrogen storage and Liquid Air Energy Storage (LAES) (Mongird1 et al., 2019). Batteries has limitations in power, relatively high cost and low power density (Fan et al., 2020)(Rahman et al., 2020). PH and CAES have special geological requirements, so cannot be easily built everywhere. Hydrogen store efficiency is still low, although technology in this field is still under development (Karellas & Tzouganatos, 2014)(Singh et al., 2023). On this background LAES seems to be very promising technology dedicated for electricity storage for system scale. LAES bases on air compression, cooling and throttling, while medium partially liquefy. Than gaseous fraction is being recycled for the beginning by a multi stream heat exchanger, when cools down the incoming air stream. Liquid air is stored. During the energy demand periods air is pumped, heated and finally expanded on the turbine connected with electricity generator (Dzido, Krawczyk, et al., 2022). Among LAES advantages no geological requirements, safe, free and non-corrosive medium, high store density, and well-known components can be mentioned (Krawczyk, Szab, et al., 2018).

Although the LAES installations have been built and operated, still there is the potential for efficiency growth. Scientists have proposed various ways of LAES efficiency increasing, from system parameters optimization (Krawczyk et al., 2016)(Krawczyk, Szabłowski, et al., 2018), by liquefaction section

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configuration (Dzido, Krawczyk, et al., 2022), residual heat application in regasification section (She et al., 2017), ending by additional circuit addition like described in (Dzido, Wołowicz, et al., 2022). In this study a special attention was paid to another key processes in the unit - cold storage.
The cold stores considered in LAES systems can be divided into two groups, constant temperature (mainly fluid tanks, like described in (Gandhi et al., 2022)(An et al., 2020)) and variable temperature (packed bed – sensible or latent heat) (Mashayekh et al., 2023)(Hamdy et al., 2019). The majority of analyzed in literature systems cooperates with constant temperature stores, as their cooperation with the whole installation seems to be easier. Among their drawbacks high costs and flammability could be enumerated. Solid-based stores are cheaper and safer, but more difficult to control (Liang et al., 2023).
The aim of this study was to develop the mathematical model of the packed-base cold store dedicated for cooperation with LAES installation. The goal of research was to examine cold storage geometries and packed bed materials, including PCMs and solid material comparison.

2 MATHEMATICAL MODEL

2.1 Base equations

Heat and mass transport in the analyzed domain should be determined with the help of base flow equations:

- continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{1}$$

- energy conservation equation

$$\frac{\partial (\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + \nabla \cdot (\rho U h_{tot}) = \nabla \cdot (\lambda \nabla T) \tag{2}$$

- where

$$h_{tot} = h + \frac{1}{2} U^2 \tag{3}$$

- momentum conservation equation

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U \otimes U) = -\nabla p + \nabla \cdot \tau \tag{4}$$

- where

$$\tau = \mu \left(\nabla U + (\nabla U)^T - \frac{2}{3} \delta \nabla \cdot U \right) \tag{5}$$

2.2 Flow model

Although low velocities occur in the analyzed domain, the in the packed bed turbulences could occur, so turbulence model needs to be used (Gbadago et al., 2020). In this study k-ω SST (equations 6-9) was selected like in analogous research (Baliga & Nikrityuk, 2023).

$$\frac{\partial u_i}{\partial t} + u_k \frac{\partial u_i}{\partial x_k} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} - \frac{1}{\rho} \frac{\partial}{\partial x_k} \left((\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i} \right) \right) \tag{6}$$

$$\frac{\partial u_k}{\partial x_k} = 0 \tag{7}$$

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_j)}{\partial x_j} = \hat{G}_k - \beta^* \rho \omega \kappa + \frac{\partial}{\partial x_j} \left((\mu + \sigma_\kappa \mu_t) \frac{\partial k}{\partial x_j} \right) \tag{8}$$

$$\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho \omega u_j)}{\partial x_j} = \frac{\gamma}{\nu} \hat{G}_k - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left((\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right) + 2\rho (1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \tag{9}$$

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2.3 Media

Air

Properties of air were established as follows:

- Density – Real gas Peng Robinson model,
- Viscosity – Sutherland model,
- Specific heat – piecewise-polynomial function,
- Thermal conductivity – piecewise-linear function based on the assumption that air is nitrogen/oxygen mixture with mass fractions 0.79 and 0.21 correspondingly. Data on isobaric properties at 1.49 bar was gathered from (National institute of standards and technology, n.d.-b).

Packed bed

Various materials could be used in cryogenic solid store (Li et al., 2013). The material selection depends on (Yang et al., 2021): operating temperature range for appropriate application, energy density (higher values preferable), thermal conductivity (higher values preferable), density (higher values preferable), degree of subcooling (or supercooling, lower values desired), corrosion resistance, stability (chemical and physical), poisonous, toxic, flammable, or explosive properties, vapor pressure (should be low) and volume change, cost and availability in large quantities.

In (Tan et al., 2022) the packed bed cold store numerical analysis are shown. In this study the storing material has the shape of equal balls, packed evenly in the tank space. The variety of cold storage packaging structures is shown in (Zhao et al., 2020), referring to phase change materials.

In this study three packed bed materials were selected, two PCMs and dolomite. Its main properties are presented in Table 1.

Various approaches to the mathematical modelling of the packed bed solid stores can be found in (Tafone et al., 2021). Generally it can be modelled as a porous zone like in (Karim & Naser, 2017), or more direct – by detailed geometry (usually equally spaced balls) consideration. The second approach is more expensive, but allows for phase change modelling, so was selected in this study.

Table 1: Packed bed material properties

Material	**Producer**	**Density**	**Transition temperature**	**Specific heat capacity**	**Thermal conductivity**	**Latent heat**
		kg/m^3	K	J/ (kg·K)	W/ (m·K)	kJ/kg
E-114	PlusIce	782	159.15	2390	0.17	107
E-65	PlusIce	1180	208.15	3280	0.56	240
Dolomite	-	2827	-	910	1.75	-

The material of encapsulation is stainless steel with 0.5 mm thickness, which has been proved to reduce the chemical instability of PCMs/ encapsulation interface (Yang et al., 2021). Thermal conductivity of steel was established as a polynomial function in Ansys Fluent according to data available in for Stainless Steel 304L (UNS S30403) (National institute of standards and technology, n.d.-a).

2.4 Geometry and mesh

As this is preliminary study, to speed-up the calculation time 2D domain was chosen. Two geometries were considered. The geometries were created based on the assumption that in both PCM cases the storage has to have similar heat capacity. As this capacity is depended on mass of storage material inside the tank, the material with smaller specific heat capacity and latent heat requires larger tank to necessitate higher mass.

Each geometry consists of the inlet and outlet zones, which are separated from the packed bed zones by aluminum porous zone. This is to prevent packed bed material motion and ensure more equal air velocity distribution at the bed inlet.

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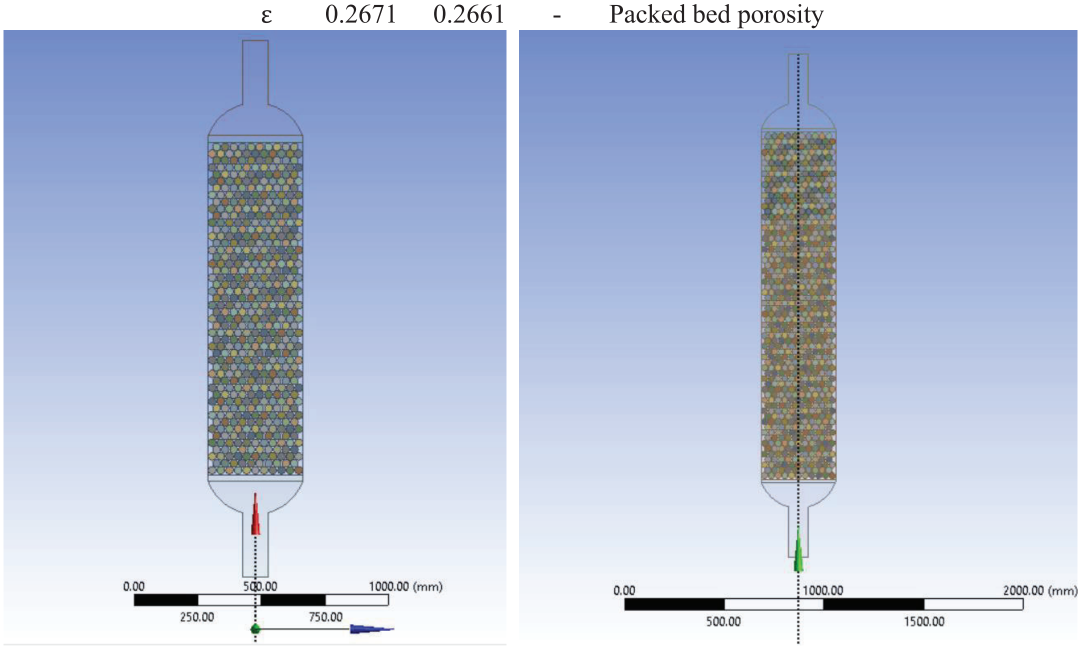
Table 2: Properties of analyzed geometries

Mark	Value A	Value B	Unit	Comment
d	30	30	mm	pebble diameter
N	378	672	-	n.o. grains
L1	1760	2520	mm	tank length
L2	980	1740	mm	packed bed length
W1	372	372	mm	tank width
W2	15	15	mm	Porous zone thickness
ε	0.2671	0.2661	-	Packed bed porosity

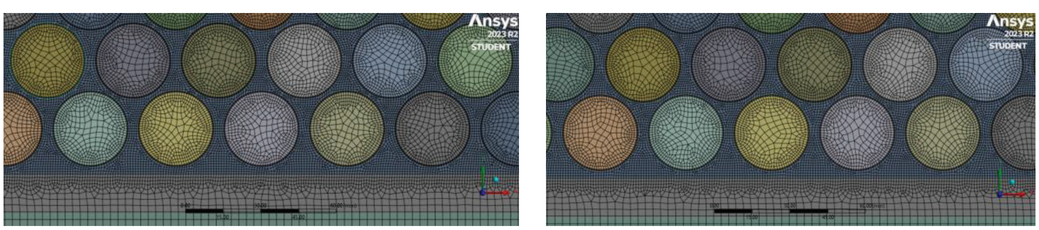


Geometry A

Geometry B

Figure 1: Analyzed geometries.

For CDF calculations the fluid domain needs to be discretized. The generated mesh is presented in the Fig. 2. Main mesh properties are summarized in Table 3.



Mesh A

Mesh B

Figure 2: Grids for geometries A and B.

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Table 3: Properties of mesh.

Parameter	Geometry A	Geometry B
Number of elements	349425	609399
Number of nodes	351087	606777
Average element quality	0.74749	0.7417
Average aspect ratio	1.8036	1.8225
Average skewness	0.16119	0.16453
Average orthogonal quality	0.96661	0.96555

2.5 Initial and boundary conditions, solver settings

During the plant discharging process (CTES charging) the air flowing into packed bed has a temperature of $T_{f\,in\,1} = 92.7$ K, the initial system temperature is $T_{sys\,ini} = 278.2$ K and the operating pressure is $P_{abs} = 1.49$ bar (Sciacovelli et al., 2017). Inlet was modelled as velocity inlet with the speed of 1.5 m/s. All walls were treated as adiabatic. Outlet was modelled as pressure outlet.
The transient calculations were conducted using SIMPLEC algorithm with spatial discretization parameters as follows: least squares cell-based gradient, 2nd order pressure discretization, 2nd order upwind density, momentum and energy discretization. Moreover, 1st order implicit transient formulation and 1st order turbulent kinetic energy and specific dissipation energy discretization was applied. Time step size was set as 0.5 s, due to high computational cost of calculations.

3 ANALYSED CASES

In this study cryogenic store charging process (LAES unit discharging) was modelled. Three cases were analyzed, which description is summarized in Table 4.

Table 4: Analyzed cases.

Case n.o.	Geometry	Comment
1	A	Material E65, CTES charge
2	B	Material E115, CTES charge
3	A	Dolomite, CTES charge

4 RESULTS

In this study, transient calculations were conducted to investigate performance of packed bed CTES (Cold Thermal Energy Storage) for various materials and conditions. Following analysis focuses on thermal behaviour, influence of geometry and material properties and fluid dynamics within the system. It was observed that the packed bed in Case 1 reached a charged state at approximately 2250 s and this duration was established as a reference time for comparing all cases. The average mass flow rates were consistent across all the cases – Case 1 at 0.01771 kg/s, Case 2 at 0.01776 kg/s and Case 3 at 0.01769 kg/s – allowing for comparison of thermal and fluid dynamics based on material properties.
It was noted that in Case 1, which utilized a material with the highest specific heat, the rate of temperature change was the slowest, requiring the most amount of energy to charge the packed bed storage (Fig. 3 and Fig. 5). In contrast, Case 3, with sensible heat material having the lowest specific heat but the highest thermal conductivity showed the quickest temperature change and by 1800s, the temperature gradient was nearly uniform across the packed bed. The thickness of thermocline was the highest for Case 3, while Case 1 exhibited the thinnest thermocline. Despite complete solidification of phase change material in Case 1 at 2200 s, a thermal front was still observed in the upper part of the packed bed, reaching temperature of around 200 K at its peak so the process could be extended. In general amount of liquid fraction over time is similar in cases 1 and 2 (Fig. 4).
Examination of mass-weighted outlet air temperatures over time showed notable differences between the three cases (Fig. 5). Case 1 exhibited the highest temperature at 2200 s equal 145 K, followed by Case 2 with 166.7 K and Case 3 displaying the lowest at 98.3 K. This fact underscores the observations about material properties critical influence made in previous sections. It is noted that in Case 1, the outlet temperature decrease rate was the most stable, implying material ability to prevent thermal fluctuations.

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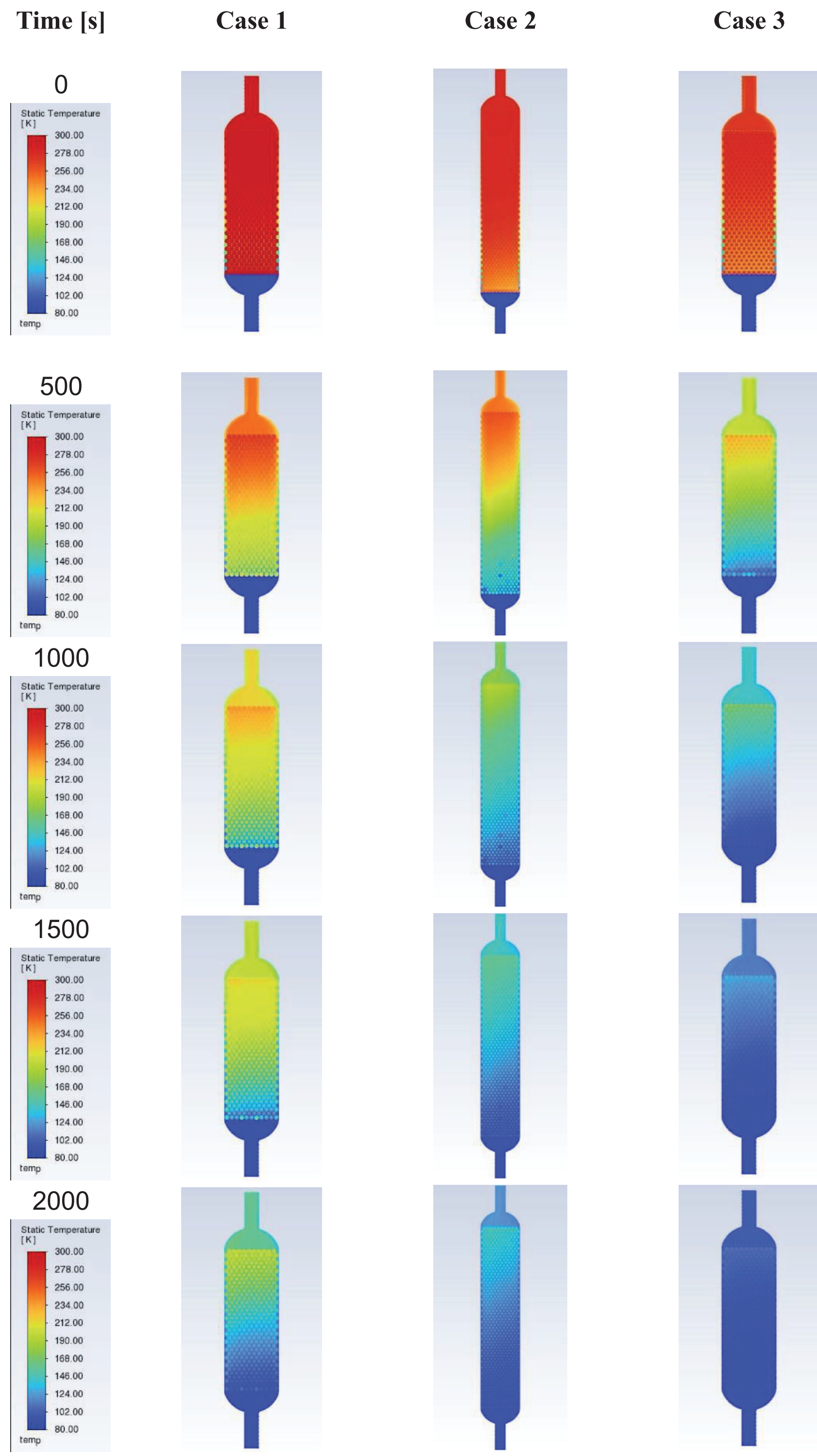

Figure 3: Contours of temperature for selected time steps.

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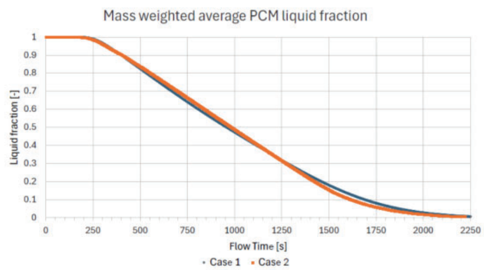

Figure 4: PCM liquid fraction as a function of flow time.

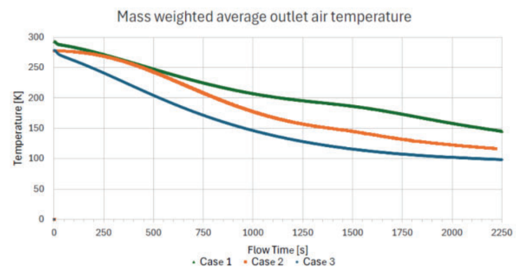

Figure 5: Mass weighted average of air temperature at the outlet.

While comparing the same geometry (A) for various materials (PCM and dolomite) it can be concluded, that in case A temperature profile is more stable over time. Moreover, the thermocline thickness is lower for PCM than for sensible material (Fig. 6 and Fig. 7).

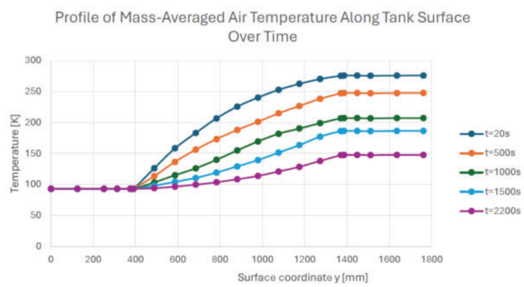

Figure 6: Temperature as a function of y coordinates (along the axis of the tank) at selected timesteps for Case 1.

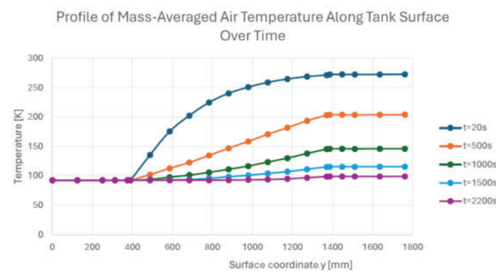

Figure 7: Temperature as a function of y coordinates (along the axis of the tank) at selected timesteps for Case 3.

5 OUTCOMES

Nowadays changes in nationals electricity generation structures, which transforms into green energy sources forces energy storage units development. One of the example energy storage systems is LAES, which efficient operation depends, among the others, on cold storage system. In this study mathematical model of the processes occurring in packed bed cold store was built and implemented in Ansys Fluent numerical software. The cold store charging process (LAES discharging mode) was considered for three cases covering two geometries and three bed materials, including two PCMs. The factors to consider beyond melting temperature are specific heat, latent heat of fusion, density, thermal conductivity. Both of studied PCMs demonstrated advantages over sensible heat material by reducing thermocline effect and thermal fluctuations. These materials not only can store more energy in the given volume, but also can improve cold energy recovery efficiency in the context of the whole LAES system ensuring more predictable temperature profile.

The presented model can be treated as a tool for further cold store development. The analysis shown potential for geometry optimization, which could be another research goal. Another aspects, which are worth to be considered are discharge mode model, more detailed geometries, different packing grids as well as 3D domain, which would yield significantly more accurate data with the cost of computational power.

6 NOMENCLATURE

F	force	[N]
T	temperature	[K]
U	vector of velocity, velocity magnitude	[m/s]
V, v	velocity	[m/s]
h	enthalpy	[kJ/kg·K]
k	kinetic energy per unit mass	[J/kg]

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p	pressure	[bar]
t	time	[s]
u	fluctuating velocity component in turbulent flow	[m/s]
v	specific volume	[m^3/kg]
β	coefficient of thermal expansion (for the Boussinesq approximation)	[K^{-1}]
$\hat{G}_k, Y_k$	original production and destruction terms for the SST model	[m^2/s^3]
λ	Thermal conductivity	[W/m·K]
μ	dynamic viscosity	[$kg \cdot m^{-1} \cdot s^{-1}$]
ρ	density	[kg/m^3]
σ	turbulence model constant	-
ω	specific dissipation rate	[s^{-1}]
$\square_i, \square_j, \square_k$	coordinates	
$\square_{tot}$	total	

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