PERFORMANCE EVALUATION OF SHELL-AND-DOUBLE CONCENTRIC TUBE HEAT EXCHANGER

By

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LIST OF ABBREVIATIONS

ASME	American Society Mechanical Engineering
CAD	Computer-Aided Design
DNS	Direct Numerical Simulation
EVM	Eddy Viscosity Models
FDM	Finite Different Method
FEM	Finite Element Method
FVM	Finite Volume Method
LMTD	Log Mean Temperature Difference
LES	Large Eddy Simulation
MAX	Maximum
PDEs	Partial Differential Equations
QUICK	Quadratic Upstream Interpolation for Convective Kinematics
RANS	Reynolds Averaged Navier Stokes
RSM	Reynolds Stress Models
RNG	Renormalization Group
STHEX	Shell-and-Tube Heat Exchanger
SDCTHEX	Shell-and-Double Concentric Tube Heat Exchanger
TEMA	Tubular Exchanger Manufacturer's Association

LIST OF SYMBOLS

A	heat transfer area (m^2)
$A_{o,cr}$	cross flow area at for one crossflow (m^2)
$A_{o,tb}$	tube-to-baffle leakage flow area (m^2)
$A_{o,sb}$	shell-to-baffle leakage flow area (m^2)
B_c	baffle cut
c_p	specific heat (J/kg.K)
d_2	inside diameter of inner tube (mm)
d_1	outside diameter of inner tube (mm)
D	diameter (mm)
D_2	inside diameter of outer tube (mm)
D_1	outside diameter of outer tube (mm)
F	correction factor
f	friction factor
G	fluid mass velocity (kg.m^2.s)
h	heat transfer coefficient (W/m^2.K)
J	correction factor for the shell side heat transfer
L	length (m)
L_{bc}	central baffle spacing (mm)
l_{tp}	tube pitch (mm)
k	turbulent kinetic energy (m^2/s^2)
m	mass flow rate (kg/s)
N	Number

N_b	number of baffle
ΔP	pressure drop (Pa)
Pr	Prandtl number
$\mathrm{P_T}$	total friction power expenditure (kW)
Q	volume mass flow rate (m^3/s)
Re	Reynolds number
T	temperature (K)
ΔT_m	logarithmic mean temperature difference (K)
U	overall heat transfer coefficient (W/m^2.K)
μ	dynamic viscosity (kg/m.s)
μ_t	turbulent dynamic viscosity (kg/m.s)
v	kinematic viscosity (m^2/s)
V	velocity (m/s)
Φ	heat transfer rate (W)
$\boldsymbol{v_t}$	turbulent kinematic viscosity (m^2/s)
λ	thermal conductivity (W/m.K)
ρ	density (kg/m^3)
σ_k	Prandtl number of k
σ_ε	Prandtl number of ε
ζ	Correction factor for the shell side pressure drop
Γ	generalized diffusion coefficient
ε	dissipation rate of turbulence (m^2/s^3) in Eqns. (3.7), (3.9), and (3.10)
	or, surface roughness in Eqn. (5.22)
	or, effectiveness in Eqns. (5.63), and (5.64).

Subscript

a	Annulus
b	Bulk
h	Hydraulic
i	inner tube side
id	Ideal
in	Inlet
min	Minimum
out	Outlet
p	Nanoparticle
s	shell side
t	tube side
w	wall side

Analisis Berangka ke atasPenukar Haba *Shell*-dan-*Double Concentric Tube*

ABSTRAK

Penukar haba *Shell*-dan-*tube* (STHEX) telah digunakan sejak beberapa dekad yang lalu. Secara konvensional untuk meningkatkan prestasi termo-hidraulik penukar haba klasik, panjang keseluruhan tiub perlu ditingkatkan. Ini menyumbang kepada kelemahan utama dari segi reka bentuk penukar haba klasik terutamanya apabila mempertimbangkan aspek ekonomi. Dalam kajian ini, analisis prestasi termo-hidraulik penukar haba *shell*-dan-*double concentric tube* (SDCTHEX) dijalankan menggunakan perisian komersial Dinamik Bendalir Berkomputer (CFD) *ANSYS FLUENT 14.0*. Model aliran gelora iaitu 3D *realizable* k-ε bersama-sama fungsi dinding *scalable* digunakan bagi keseluruhan simulasi berangka. Kebergantungan termofizik bendalir kerja terhadap suhu digunakan dan penukar haba dianalisis dengan mempertimbangkan pemindahan haba konjugat daripada minyak panas di dalam shell dan tiub dalaman kepada bendalir kerja di bahagian anulus. Tujuan pengesahan ke atas pekali pemindahan haba dan kejatuhan tekanan telah dilakukan, dimana kaedah *Bell-Delaware*, *Gnielinski*, dan *Haaland* kolerasi dibandingkan dengan nilai-nilai simulasi CFD bagi SDCTHEX dan STHEX klasik. Model SDCTHEX kemudiannya dibanding dengan model STHEX klasik bagi prestasi termo-hidraulik pada kadar alir jisim cecair panas yang berbeza. Seterusnya, kesan diameter tiub dalaman yang berbeza dan susunan aliran yang berbeza (aliran bertentangan dan selari) bendalir kerja ke atas prestasi SDCTHEX disiasat. Selain daripada itu, kesan pemindahan haba dan kejatuhan tekanan Al_2O_3/air bendalir nano pada kepekatan isipadu serbuk nano yang berbeza dan kadar alir yang berbeza didalam bahagian annulus SDCTHEX juga dianalisis. Keputusan menunjukkan bahawa peratus peningkatan purata keseluruhan kadar pemindahan haba per kejatuhan tekanan keseluruhan SDCTHEX dengan diameter tiub dalaman bersamaan dengan 8/12 mm / mm, hampir 343 % lebih tinggi daripada STHEX. Kadar pemindahan haba keseluruhan setiap kejatuhan tekanan keseluruhan SDCTHEX juga didapati sensitif kepada diameter tiub dalaman. Diperhatikan bahawa untuk kadar aliran jisim 22.5 kg / s, nilai $\Phi/\Delta P$ adalah paling maksimum kira-kira 400 % lebih tinggi pada diameter tiub dalaman 12/16 mm / mm berbanding dengan STHEX. Selain daripada itu, prestasi termo-hidraulik bagi susunan aliran bertentangan bendalir kerja juga didapati lebih tinggi daripada susunan aliran selari bendalir bekerja yang diuji pada setiap kadar aliran jisim bagi bendalir panas. Ini menunjukkan bahawa SDCTHEX mungkin menjadi pilihan yang ideal untuk menggantikan STHEX klasik dalam aplikasi industri penukar haba. Untuk kesan bendalir nano, keputusan menunjukkan bahawa pada *Re* yang sama, prestasi pemindahan haba meningkat dengan meningkatkan kepekatan isipadu serbuk nano dan ia mempunyai nilai yang lebih tinggi berbanding dengan air. Tetapi jika dibandingkan pada kadar aliran jisim yang sama, bendalir nano pada setiap kepekatan isipadu serbuk nano tidak menunjukkan peningkatan pemindahan haba berbanding air.

Numerical Analysis of Shell-and-Double Concentric Tube Heat Exchanger

ABSTRACT

Shell-and-tube heat exchangers (STHEX) have been used for several decades. Conventionally to increase the thermo-hydraulic performance of classical heat exchangers, overall length of tubes has to be increased. This contributes major disadvantage in term of classical heat exchangers design particularly considering economical aspect. In this study, the thermo-hydraulic performance analysis of a shell-and-double concentric tube heat exchanger (SDCTHEX) is carried out using commercially the available Computational Fluid Dynamic (CFD) software ANSYS FLUENT 14.0. A 3D realizable k–ε turbulence model with *scalable wall function* treatment is used for the whole numerical simulations. Validation on heat transfer coefficient and pressure drop are done, where the *Bell-Delaware* method, *Gnielinski*, and *Haaland* correlations are compared with CFD simulation values of SDCTHEX and classical STHEX. The SDCTHEX model is then compared with classical STHEX model for their thermo-hydraulic performances for different mass flow rates of the hot fluid. Next, the effects of different inner tube diameters and different arrangement (counter and parallel flows) flows of working fluids flows on the performance of SDCTHEX are investigated. Other than that, the effects of the heat transfer and pressure drop of Al_2O_3/water nanofluid at different Al_2O_3 nanoparticle volume concentrations and flow rates flowing inside annulus side of SDCTHEX are also analysed. It is observed that, the percentage of overall heat transfer rate per overall pressure drop of SDCTHEX with inner tube diameter equal to 8/12 mm/mm, is increased nearly 343 % higher than that of STHEX. Also, the overall heat transfer rate per overall pressure drop of SDCTHEX is sensitive to inner tube diameter. It is found that $\Phi/\Delta P$ for the mass flow rate of 22.5 kg/s is for to be maxed about 400 % higher at inner tube diameter of 12/16 (mm/mm) with respect to the STHEX. On the other hand, the thermo-hydraulic performance for counter flow arrangement of working fluid is also found higher than that of parallel flow arrangement of working fluid at any hot fluid mass flow rate. For the nanofluid effect, the results obtained showed that at the same *Re*, the heat transfer performance increases by increasing the nanoparticle volume concentration and it's valued higher when compared with water. But when compared at the same mass flow rate, the nanofluid at any nanoparticle volume concentration does not show any enhancement on heat transfer when compared with water.

CHAPTER 1

INTRODUCTION

Most engineering processes either in light or heavy industries involve heat energy. One such equipment used in production and absorption of heat energy is called heat exchanger. In industries, heat exchangers are widely used for chemical processing, electricity generation, space heating, air conditioning, and refrigeration.

A heat exchanger is a device used for transferring heat energy between two or more fluids that possess different temperature and separated by solid wall (thin wall). The mechanism of the heat energy transfer in a heat exchanger is shown in Fig. 1.1 involving two working fluids (i.e. cold and hot fluids) and separated by a thin wall. In conventional heat exchanger, heat energy is transferred by a combination of convection which is between fluids (cold and hot) and wall, and conduction through the thin wall from hot fluid to cold fluid.

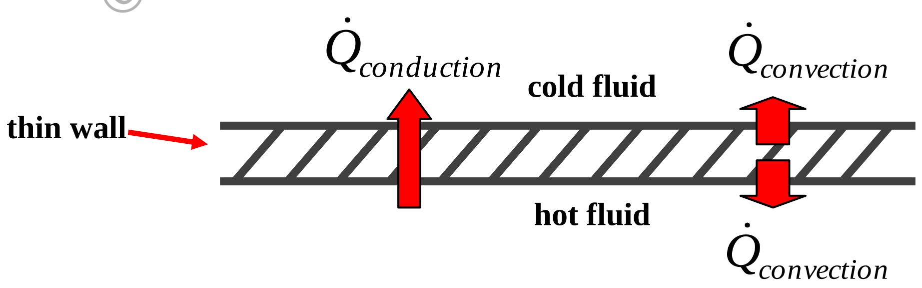


Figure 1.1: Heat energy transfer mechanism for two working fluids in a conventional heat exchanger

Heat exchangers are classified based on four criteria which are (a) transfer process, (b) number of fluids, (c) construction, (d) flow arrangement, and (e) heat transfer mechanism. Based on those criteria, the common examples of the heat exchangers are used in industries are evaporator, condenser, shell and tube, automobile radiators, cooling tower, and double tube/pipe.

More than 60 % of the market share in heat exchanger industry belongs to the shell-and-tube heat exchanger (STHEX). The factors, are as follows (Das, 2005):

i. They are suited for higher-pressure (over 30 kgf/cm^2) and higher-temperature (over 260°C) applications.

ii. The design and manufacturing procedures for this type is well established and certified by TEMA (Tubular Exchanger Manufacturer's Association) and ASME (American Society of Mechanical Engineers).

iii. For this heat exchanger type, there are well established thermal design methods to predict its performance such as *Bell-Delaware* and *Kern*.

1.1 Shell-and-Tube Heat Exchangers

Most of heat exchangers that are widely used in industrial process such as in Oil & Gas industry, food industry, chemical industry and air-conditioning are the STHEX type. In this type of heat exchanger, heat energy is transferred from working fluid flowing in the tube side to working fluid flowing in the shell side by conduction through the tube wall. The heat energy transfer, depending on the fluid arrangement, can happen either from the tube side to shell side or vice versa. The working fluids on either the shell or the tube side can be in the form of liquids or gases. A heat transfer area should be maximised in order to transfer heat to the overall heat exchanger system efficiently. Working fluids for STHEXs involving only one phase fluid (either liquid or gas) on each side are called single-phase heat exchangers, where two-phase are usually called as condensers or boilers. Figure 1.2 shows the main components of STHEX type. The detail explanations of them are briefly described in the following section.

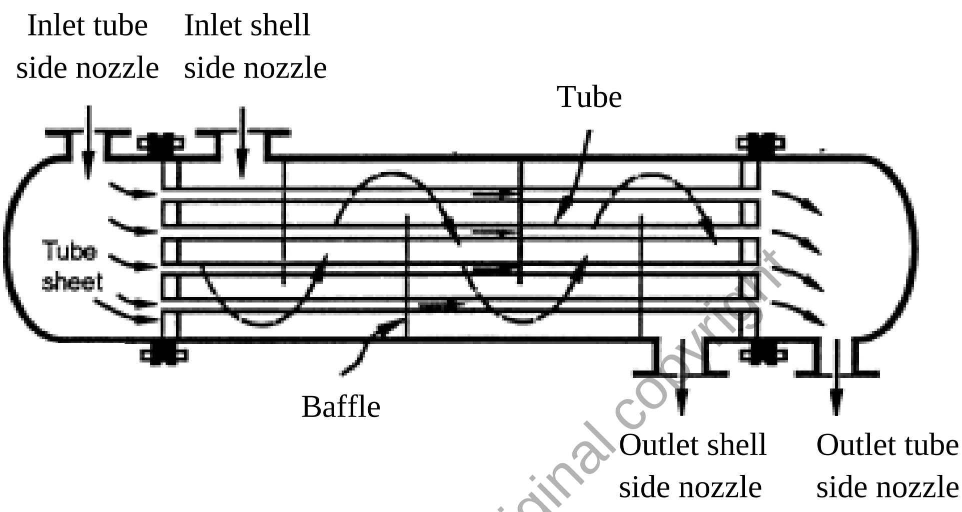


Figure 1.2: STHEX main components

1.1.1 Tubes

The function of the tubes in heat exchanger is to allow the heat transfer processes in term of conduction and convection occur between fluid in the tube side and the another fluid in shell side at the outer surface of tubes bundles. Tube pitch, tube thickness, and tube length are major characteristics from the point of view of thermal design features. Straight and U tubes are most common type of tube bundles in power and process industry exchanger.

1.1.2 Tube Sheets

Tube sheets are used to hold bundle of tubes in a STHEX. It is generally a circular metal plate that has been holes and to hold the tubes in place based on the desired tube layout. In order to make sure no clearance between tube sheet and tubes resulting in shell side leakage, the metal tube ends are forced to move into the grooves forming using several methods such as by hydraulic/pneumatic expansion of tubes, welding of tubes, and rolling the tubes. The most common method to attach between tube sheet and tube bundles is by rolling the tubes. In this method, two or more grooves are created on tube sheet in order to hold the tubes (Mukherjee, 1998) as shown in Fig. 1.3.

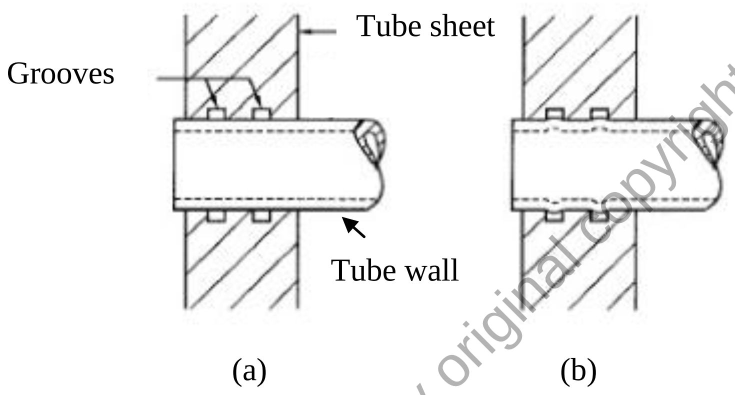


Figure 1.3: Rolling method between tube sheet and a tube: (a) before; (b) after (Mukherjee, 1998)

1.1.3 Shell side/tube side nozzles

The inlet and outlet for the working fluid the flowing inside tube and shell sides, is called as nozzles. Normally, their functions are to collect or distribute the working fluid in STHEX. The inlet and outlet for the shell-and-tube sides basically is circular pipe with uniform cross section mounted to the shell channel.

1.1.4 Baffles

There are two main functions of baffles (Sekulić & Shah, 1995):

- Fixing of the tubes in the proper position during assembly and support the tubes during vibration caused by normal flow on the tube bundles.

- Drive of the shell side flow from counter to cross flow the tube field in order to promote the turbulence so that increasing the heat transfer performance.

The various baffles type used in STHEX are shown in Fig. 1.4, and the most commonly used is segmental baffle type. The selection of baffle cut, spacing, and type are influenced mostly by flow-induced vibration, tube support, allowable pressure drop, desired heat transfer rate, and flow rate (Shah & Sekulić, 2003). To make sure that the adjacent baffles overlap at least one full baffle tube row, the segmental baffle cut must be less than half of the shell inside diameter. The baffles cut of 20 to 25 % of shell inside diameter is common for liquid flows on the shell side due to produce a good heat transfer with the reasonable pressure drop. In order to minimize the pressure drop for low pressure gas flow, normally the baffle cut of 40 to 45 % is chosen (Mohammadi, 2011). The optimum ratio of baffle spacing to shell inside diameter that will results in the highest efficiency that is normally between 0.3 and 0.6 (Mukherjee, 1998).

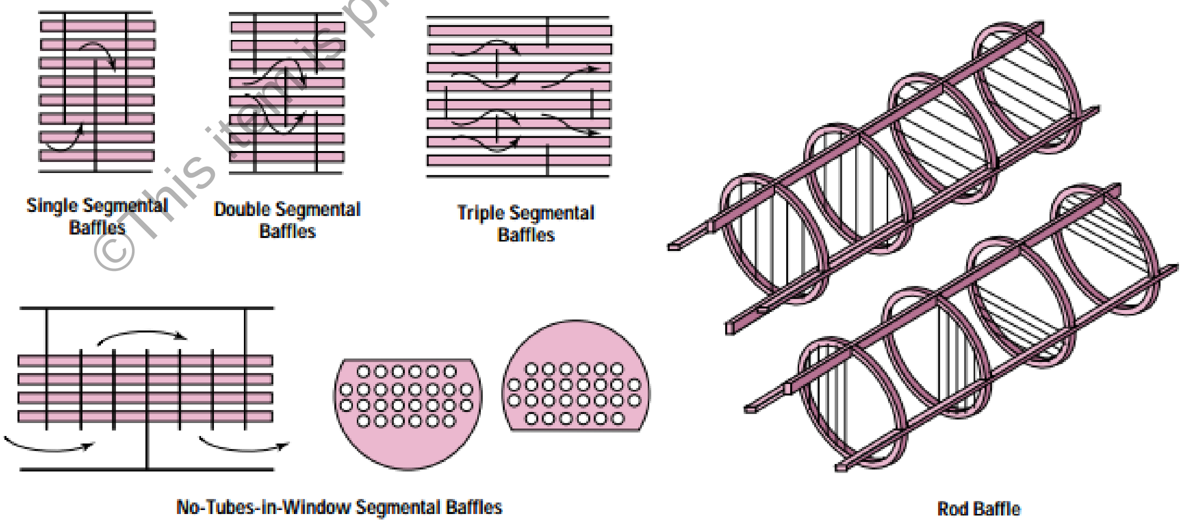


Figure 1.4: Types of baffles (Mukherjee, 1998)

1.2 Tubular Exchangers Manufacturers Association (TEMA) Design Code

Several of constructions are available in STHEX designs based on desired heat transfer, pressure drop and so on. The pressure inside of a STHEX is designed in accordance with pressure vessel design codes such as BSS (British Standards Specifications) 5500, ASME section VII, and so on, but a pressure vessel code alone cannot be expected to deal with all the special features of STHEXs. To give protection and guidance to purchaser, fabricators, and designers, a supplementary code is desirable that provides minimum standards in guarantees, design, maintenance, operation, installation, inspection, testing, tolerances, fabrication, corrosion allowances, thickness, and material for STHEXs (Hewitt, 1987). A widely accepted standard is published by the TEMA which is intended to supplement the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1. TEMA has produced a standard notation system to differentiate types of STHEX and this selection process is primarily thermal design decision. The different type of STHEX will produced different flow paths in the shell side. By this standard, three letters arrangement of STHEXs has been developed. The first letter represents the front head design, the second represents the shell design and the third letter represents the rear head design. Seven types of shell designs, developed by TEMA which are E, F, G, H, J, K, and X are illustrated in 'APPENDIX'. Of the various shell design as mentioned above, the most common one is E type. In E type, pure counter current flow defined when a single tube pass considered as shown in Fig. 1.5. This flow arrangement will increases mean temperature difference and effectiveness of the heat exchanger (Shah & Sekulić, 2003).

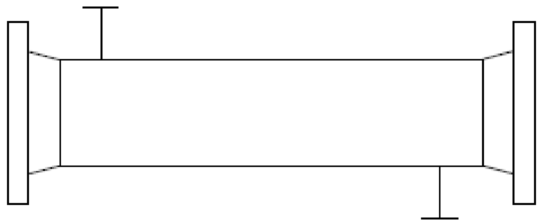
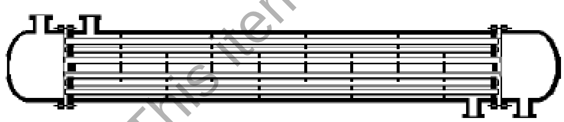


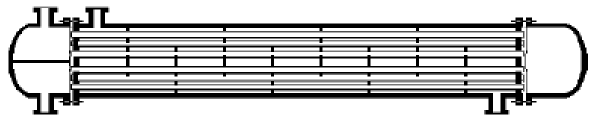
Figure 1.5: Schematic design of E-Shell based on TEMA notation system

1.2.1 Shell-and-Tube Heat Exchangers with E-Shell

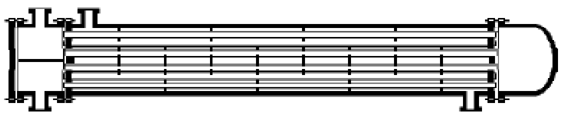
The most common design of the shell side of STHEXs is the E-shell due to its simplicity, its wide operating temperatures and pressures range, driving force and low cost (Shah & Sekulić, 2003). To increase the heat transfer performance on the tube side, the multiple passes of the tubes arrangement must be selected but this arrangement decreases the *F* factor or heat exchanger effectiveness due to some tube passes being in parallel flow compared with single pass tube arrangement (Shah & Sekulić, 2003). Figure 1.6 shows some typical E-shell arrangements based on TEMA notation system using three letter designs.



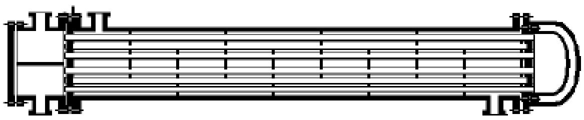
(a) BEM STHEX with one tube side pass



(b) BEM STHEX with two tube side passes



(c) AEM STHEX with two tube side passes



(d) AES STHEX with split ring (floating head with backing device) and two tube side passes

Figure 1.6: Schematic representation of typical TEMA STHEX with E-shell (Mohammadi, 2011)

1.3 Problem Statement

Shell-and-tube heat exchangers are being used for several decades. Conventionally to increase the thermo-hydraulic performance of the classical heat exchangers, overall length of tubes has to be increased. This contributes major limitation in term of classical heat exchangers design particularly considering economical aspect. As a consequence the floor area must be large enough to accommodate the entire length of these devices. Further, the increase of the tube length will require more number of baffles which will result in the increase of shell side pressure drop (Das, 2005).

Due to this concern, the single tube bundles have been replaced by double-concentric tube bundles in STHEX. As a result, the heat exchanger device is called a shell-and-double concentric-tube heat exchanger (SDCTHEX) which has three working fluids, three inlets, as well as three outlets. The analytical study has shown that this heat exchangers has a better performance in terms of its size (length of tubes) when compared to that of a classical STHEXs. From the open literatures (discussed in Chapter 2), there is no serious attempts are made to investigate performance of SDCTHEX in detail. Thus, it is interesting to investigate and visualize the thermo-hydraulic performance of SDCTHEX in this study.

1.4 Research Objectives

Objectives of the research are as the following:

i. To determine the thermo-hydraulic performance of the shell-and-double concentric tube heat exchanger (SDCTHEX) and the classical shell-and-tube heat exchanger (STHEX) under the same operating conditions using numerical simulation.