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Modeling and Study of a Printed Circuit Heat Exchanger for Brayton Power Cycles Using Supercritical CO_2 Mixtures as Working Fluid

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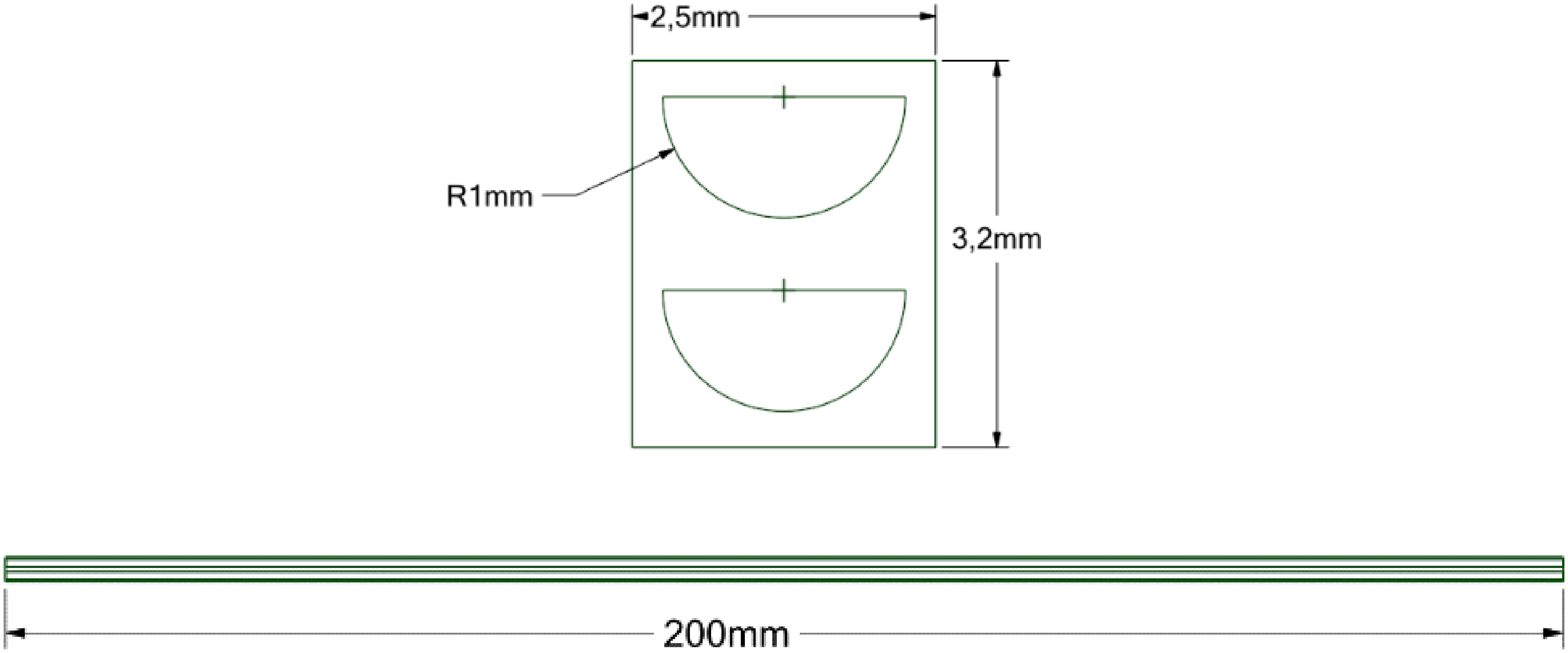
Introduction

This study focuses on the CFD modeling and analysis of a PCHE for fully turbulent conditions.

A comparison between pure supercritical carbon dioxide and s-CO_2 mixtures (s-CO_2 /COS, s-CO_2 /H_2S, s-CO_2 /NH_3, and s-CO_2 /SO_2) is carried out.

SYSTEM DESCRIPTION



Geometry measurements; (a) front view, (b) side view.

MATHEMATICAL MODELING

Continuity equation:

$$\frac{\partial(\rho u_j)}{\partial x_j} = 0 \qquad (1)$$

Momentum equation:

$$\rho \frac{\partial(u_i u_j)}{\partial x_j} = -\frac{\partial p_i}{\partial x_j} + \mu \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \qquad (2)$$

Energy equation:

$$\frac{\partial}{\partial x_j}\left[u_j(\rho E + p)\right] = \frac{\partial}{\partial x_j}\left(\left(k_f + k_t\right)\frac{\partial T}{\partial x_j}\right) \qquad (3)$$

The energy equation for the solid domain:

$$\frac{\partial}{\partial x_j}\left(k_s \frac{\partial T}{\partial x_j}\right) = 0 \qquad (4)$$

MATHEMATICAL MODELING

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad (5)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \quad (6)$$

MATHEMATICAL MODELING

$$P = \frac{RT}{V - b + c} - \frac{a(T)}{V(V + b)} \qquad (7)$$

$$a(T) = a_0 T_r^{-n} \qquad (8)$$

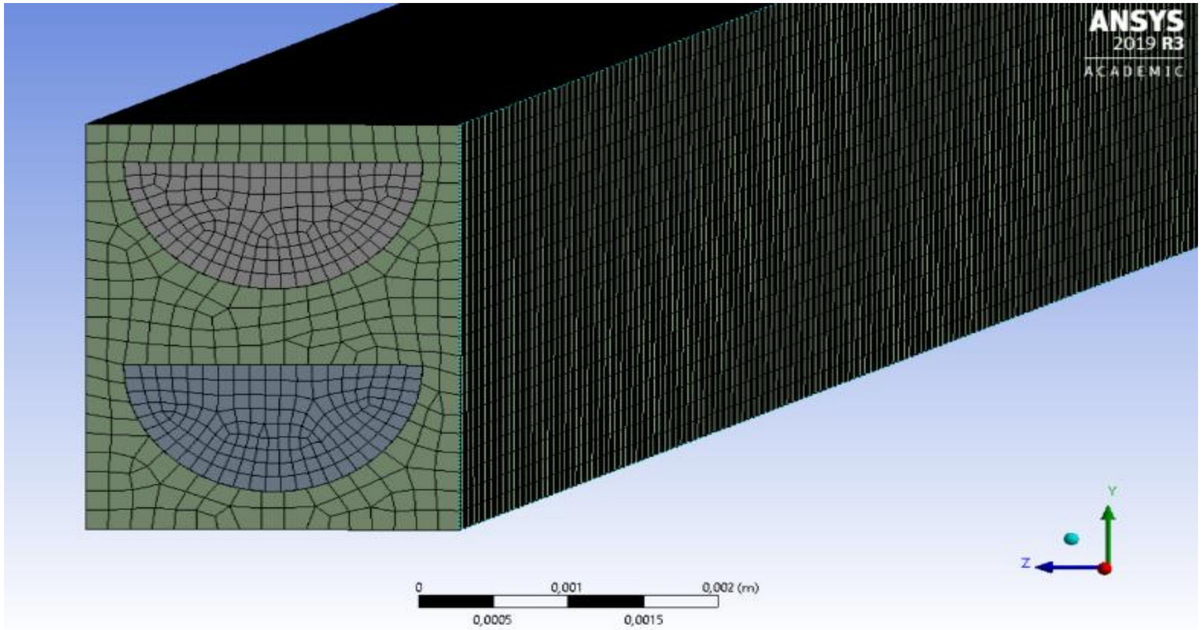
$$c = \frac{RT_c}{P_c + \frac{a_0}{V_c + (V_c + b)}} + b - V_c \qquad (9)$$

$$n = 0{,}4986 + 1{,}1735\omega + 0{,}4754\omega^2 \qquad (10)$$

$$a_0 = 0{,}42747 R^2 T_c^2 / P_c \qquad (11)$$

$$b = 0{,}08664 R T_c / P_c \qquad (12)$$

MATHEMATICAL MODELING



$$y^{+} = \frac{y u_{\tau}}{\nu} \quad (13)$$

$$u_{\tau} = \sqrt{\frac{\tau_{w}}{\rho}} \quad (14)$$

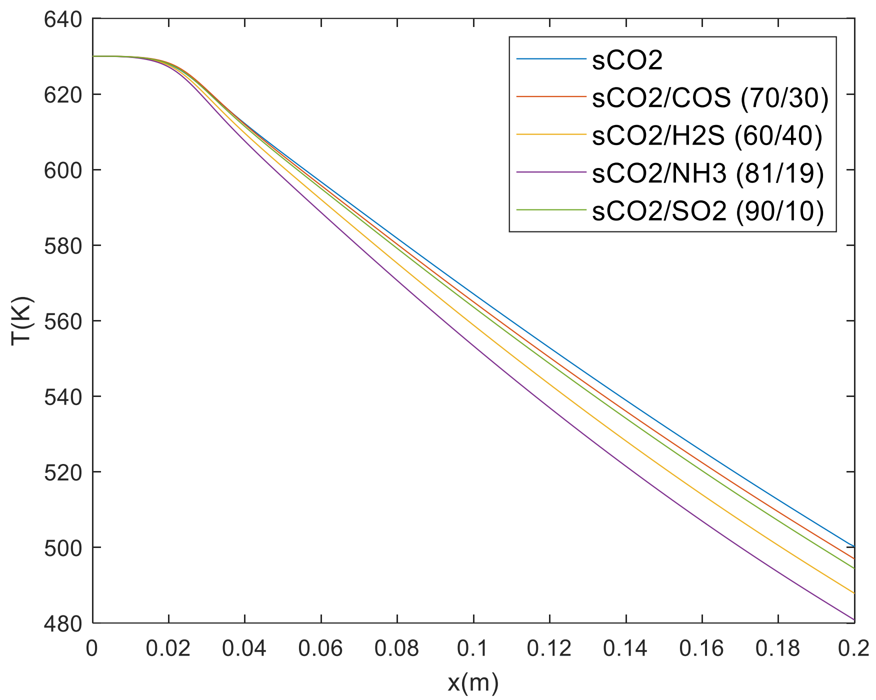
$$u^{+} = \frac{1}{k} ln(y^{+}) + B \quad (15)$$

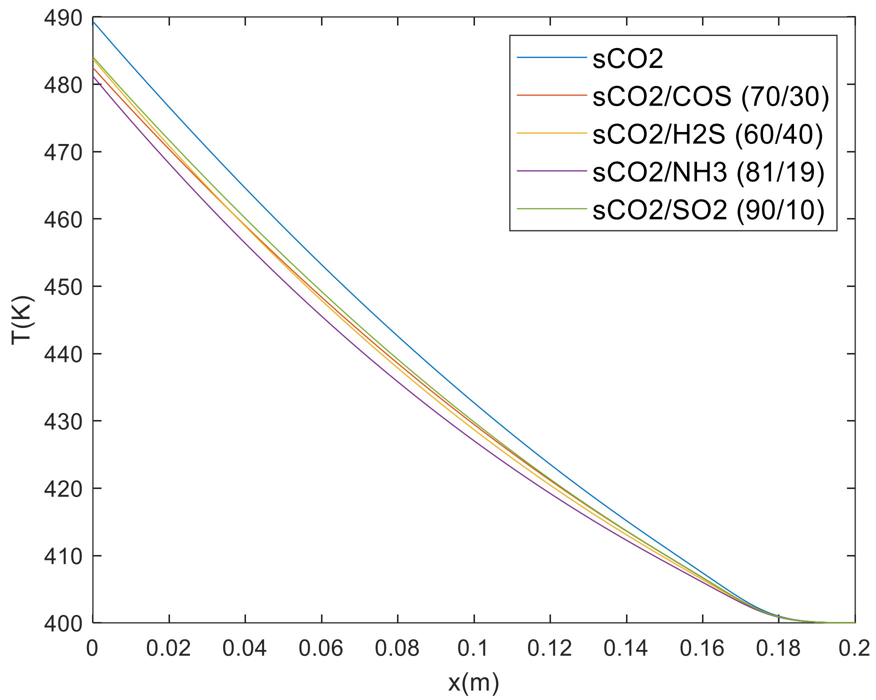
BOUNDARY CONDITIONS

Boundary	Boundary condition
Flow inlet	Inlet velocity
Flow outlet	Outlet pressure
Upper wall	Periodic
Bottom wall	Periodic
Sidewalls	Adiabatic
Front wall	Adiabatic
Back wall	Adiabatic

Property	Cold s-CO_2	Hot s-CO_2
Temperature [K]	400	630
Pressure [bar]	225	90
Velocity [m/s]	0,842	4,702

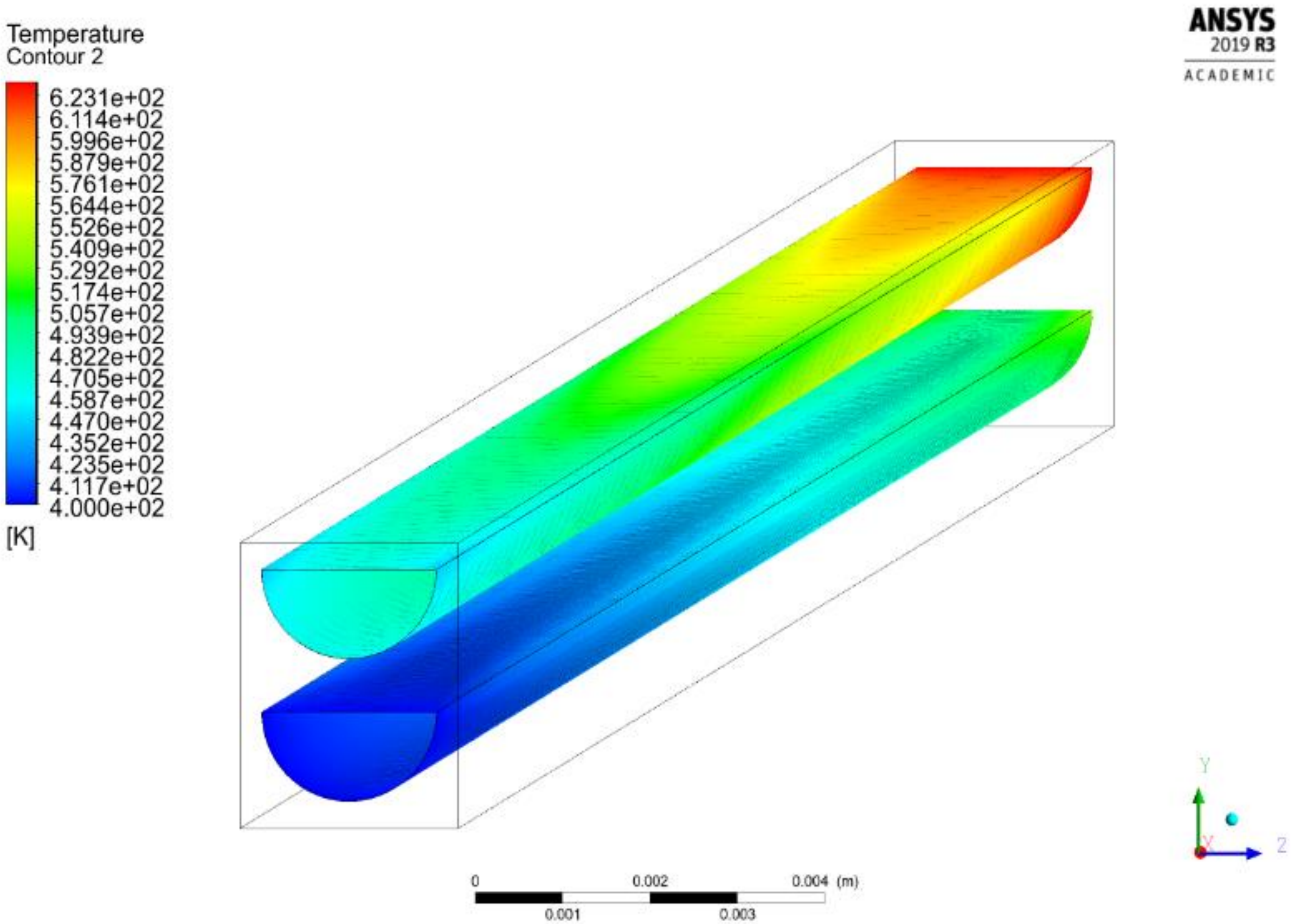
RESULTS AND DISCUSSION





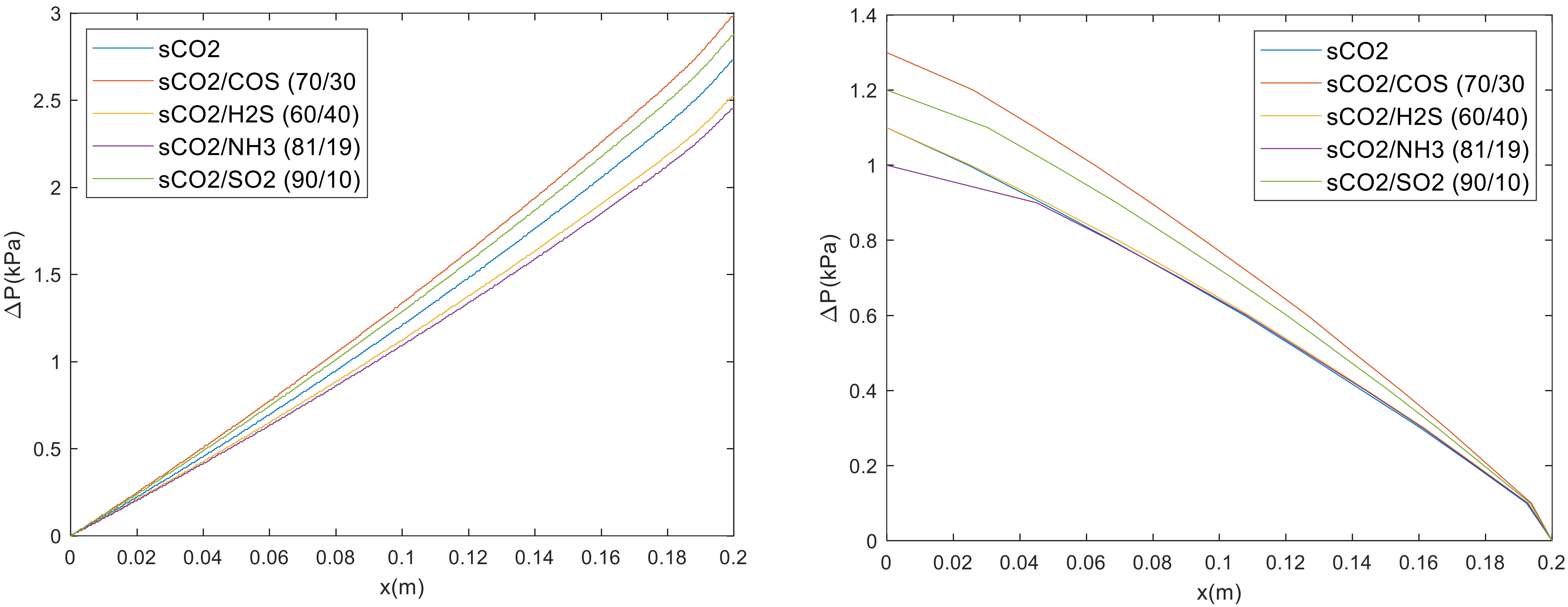
Temperature profile of the different mixtures; (a) hot fluid; (b) cold fluid.

RESULTS AND DISCUSSION



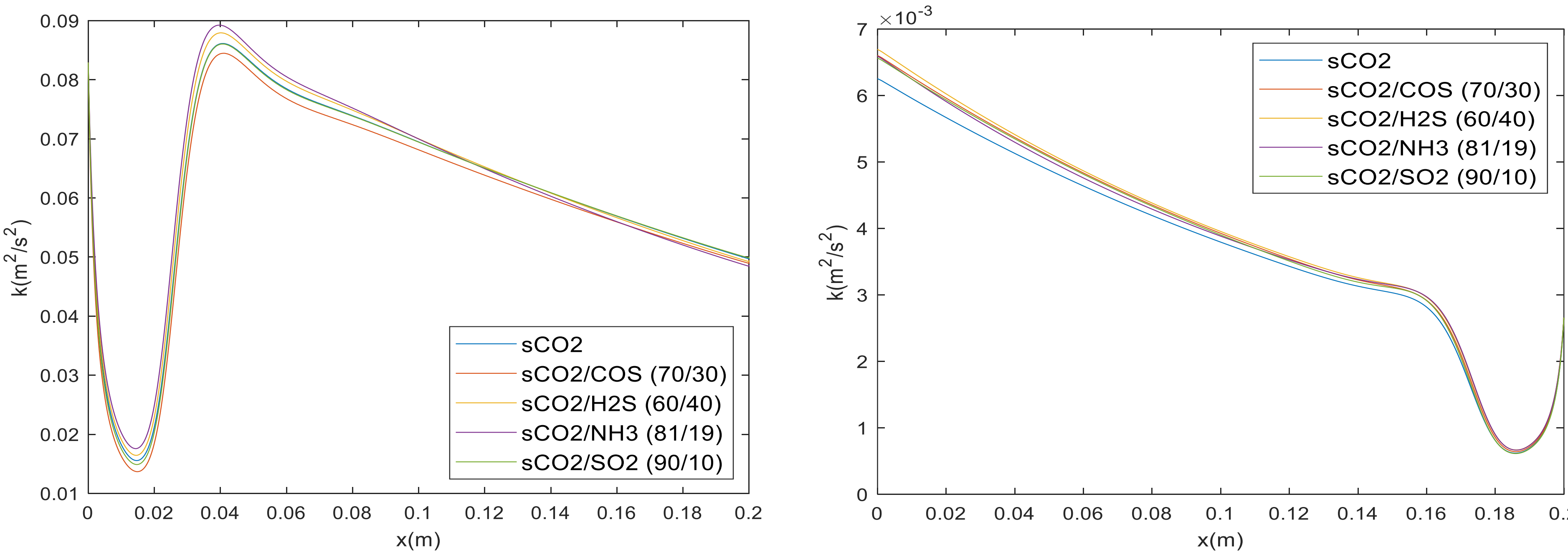
Temperature distribution in the fluid domain of the s-CO2/NH3 mixture.

RESULTS AND DISCUSSION



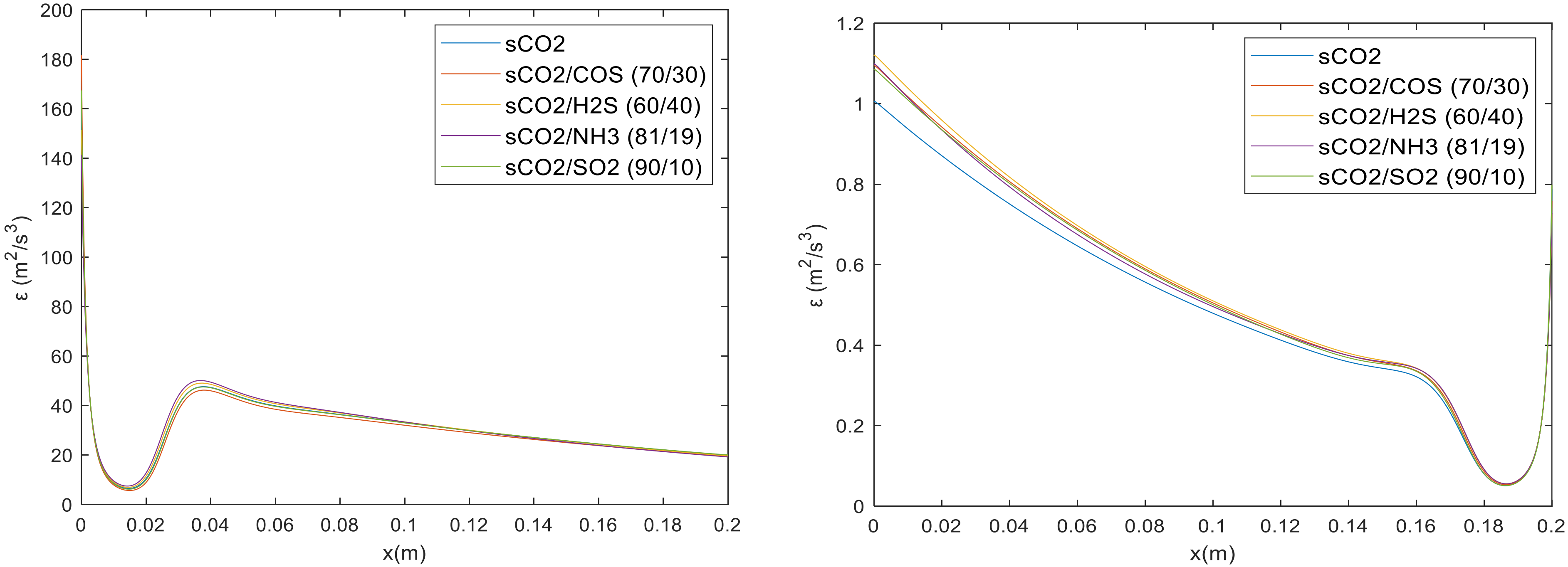
Pressure drop of the different mixes in the straight channels; (a) hot fluid; (b) cold fluid

RESULTS AND DISCUSSION



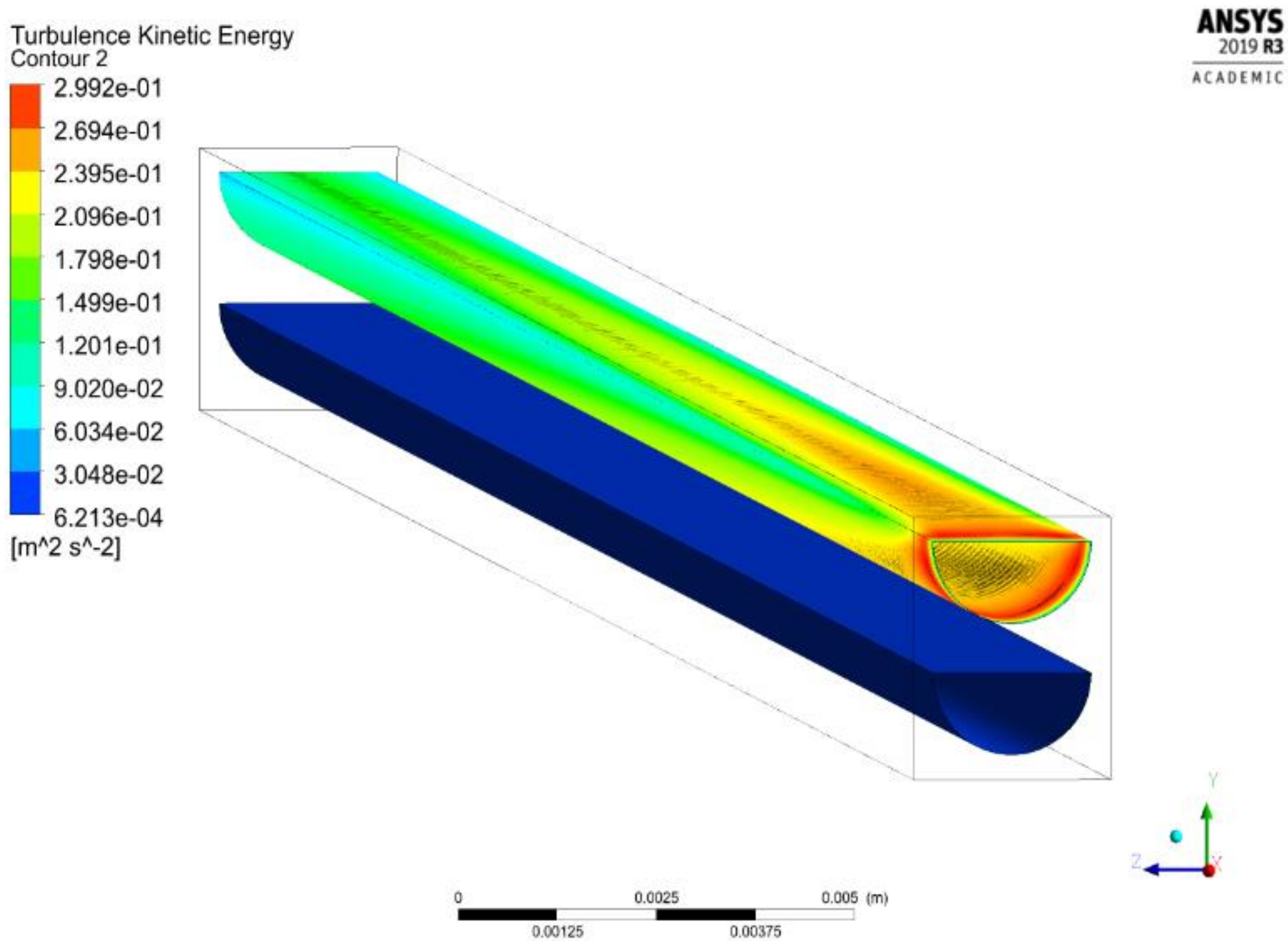
Turbulent kinetic energy of the different mixtures in the straight channels; (a) hot fluid; (b) cold fluid.

RESULTS AND DISCUSSION



Dissipation rate of the different mixtures' turbulent kinetic energy in the straight channels; (a) hot fluid; (b) cold fluid.

RESULTS AND DISCUSSION



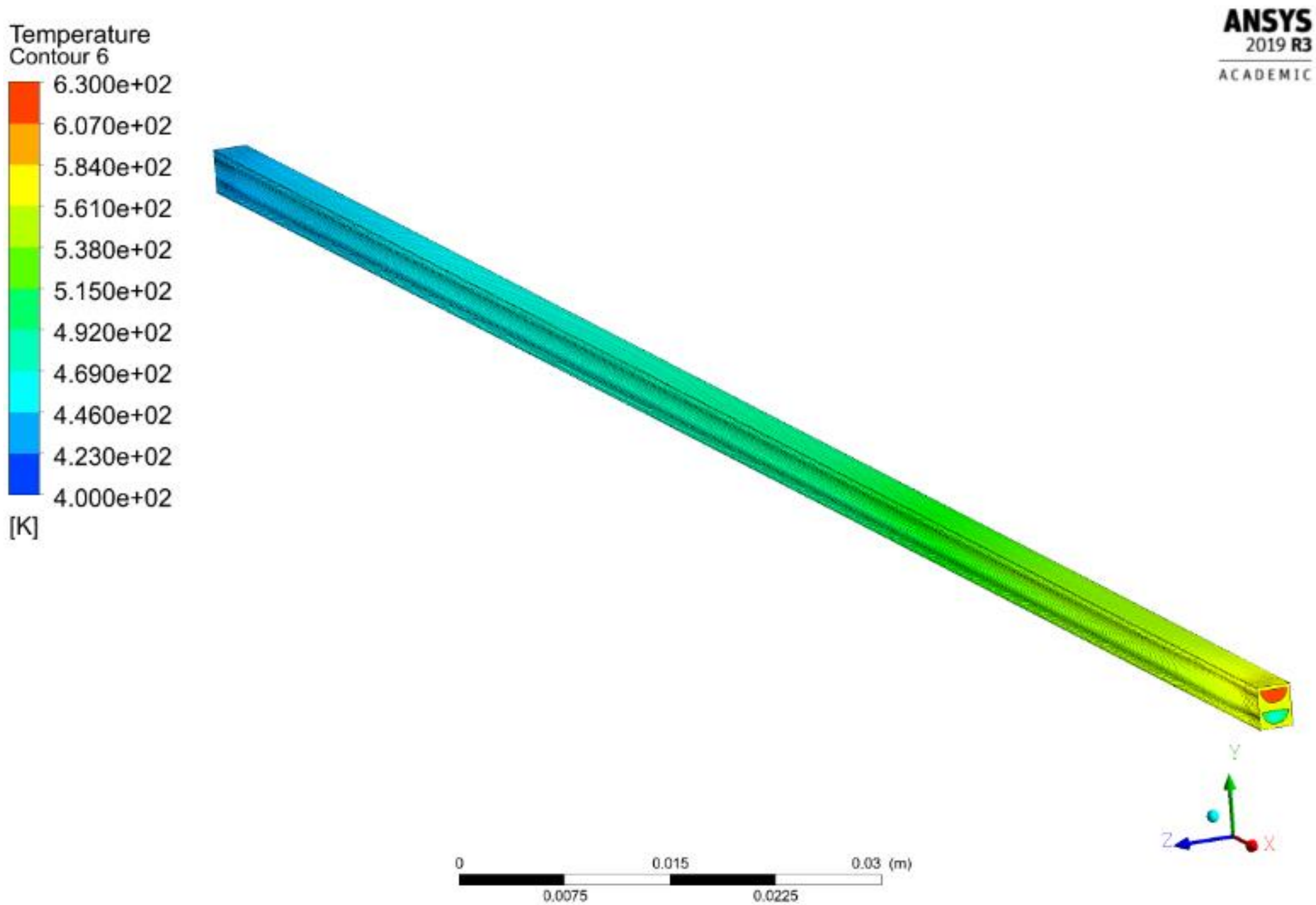
Turbulent kinetic energy of hot flow and cold flow for the s-CO2/NH3 mixture.

RESULTS AND DISCUSSION

	Surface heat flux [kW/m^2]
s-CO_2	90.037
s-CO_2/COS (70/30)	103.66
s-CO_2/H_2S (60/40)	91.25
s-CO_2/NH_3 (81/19)	92.32
s-CO_2/SO_2 (90/10)	98.64

Surface heat flux of each mixture.

RESULTS AND DISCUSSION



Temperature along the solid boundary of the mixture exchanger s-CO2/COS.

RESULTS AND DISCUSSION

	ΔT_{ml} [K]	U $[W/m^2 \cdot K]$	Area $[m^2]$
s-CO_2	119.443	854.067	14.704
s-CO_2/COS (70/30)	120.491	968.866	12.849
s-CO_2/H_2S (60/40)	114.586	898.874	14.563
s-CO_2/NH_3 (81/19)	111.368	939.606	14.335
s-CO_2/SO_2 (90/10)	118.315	940.831	13.475

Relevant parameters of each mixture

RESULTS AND DISCUSSION

	Reynolds (cold)	Reynolds (hot)	Nusselt (cold)	Nusselt (hot)	$\underline{h}_{cold}$ $[W/m^2K]$	$\underline{h}_{hot}$ $[W/m^2K]$
s-CO_2	21080.52	23833.96	43.706	43.986	1851.094	1660.921
s-CO_2/COS (70/30)	20772.70	27341.45	47.386	51.536	2149.123	1857.850
s-CO_2/H_2S (60/40)	20279.52	22764.62	42.870	43.216	2038.296	1685.415
s-CO_2/NH_3 (81/19)	20045.90	21230.44	40.957	40.276	2236.681	1698.906
s-CO_2/SO_2 (90/10)	21555.17	25091.09	46.520	48.153	2107.748	1786.100

Average surface heat transfer coefficient, Reynolds number, and Nusselt number of the different mixtures

CONCLUSIONS

- ✓ It is concluded that the increase in performance in the Brayton cycle of certain mixtures that raise the temperature of the critical point is directly correlated with the increase in the performance of a PCHE recuperator.
- ✓ All the mixtures studied have shown better global heat transfer coefficients than pure supercritical carbon dioxide, which represents a reduction for the mixtures sCO_2/COS (70/30), **s-**CO_2/H_2S (60/40), **s-**CO_2/NH_3 (81/19) and **s-**CO_2/SO_2 (90/10) of 12.62%, 0.96%, 2.51%, and 8.36%, respectively in the total heat exchange area.
- ✓ This inference can be extrapolated directly into considerable economic savings for high power ranges, which can be critical in driving research fields related to solar power generation supplemented with supercritical Brayton power cycles.
- ✓ These results yield highly relevant conclusions since they confirm the possibility of continuing Brayton cycles' improvement using PCHE exchangers as regenerators. It is, therefore, a step forward in the investigation of supercritical Brayton cycles, which in the future may represent important advances in the mitigation of greenhouse gas emissions.

THANKS FOR YOUR ATTENTION

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