Helical Coil Heat Exchanger Design for Hydrogen Storage Systems

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Introduction

- DOE targets (2010)
  - System Gravimetric capacity = 0.045 kg H2/kg system
  - System Volumetric capacity = 28 g/L system
- Sodium Alanate system
  - theoretical maximum storage capacity = 0.056 kg H2/kg alanate
  - observed maximum capacity = 0.039
  - Capacity for 10.5 minutes refueling time ~ 0.03-0.033
- Heat exchanger and balance of plant will occupy additional weight and volume
- Compact heat exchanger design is essential

Sodium Alanate System

$NaAlH_4 \leftrightarrow 1/3Na_3AlH_6 + 2/3Al + H_2$

$$\Delta H = -37 \text{ kJ/mole } H_2$$

$$r_{1a} = K_{oa1} \exp\left(-\frac{E_{aa1}}{RT}\right) \ln\left(\frac{P_{bed}}{P_{eq1}}\right) (3.9 - H\ wt\%)^2;\ (1.67 < H\ wt\% < 3.9)$$

$1/3Na_3AlH_6 \leftrightarrow NaH + 1/3Al + 1/2H_2$

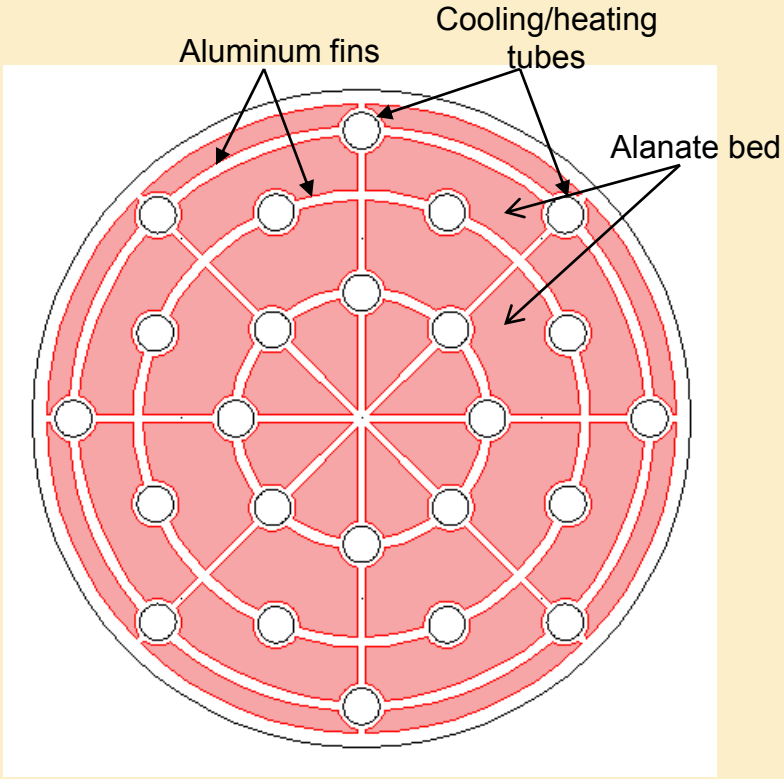
$$\Delta H = -42 \text{ kJ/mole } H_2$$

$$r_{2a} = K_{oa2} \exp\left(-\frac{E_{aa2}}{RT}\right) \ln\left(\frac{P_{bed}}{P_{eq2}}\right) (1.67 - H\ wt\%);\ (H\ wt\% < 1.67)$$

- Large heat of absorption/desorption
- Reactions proceed significantly for T> 80 C
- Hence cooling fluid has to supplied at ~100 C and at the same time provide cooling to remove the high heat of absorption

Heat exchanger design is challenging

Earlier Design at GM



Cross-sectional view of shell and tube heat exchanger

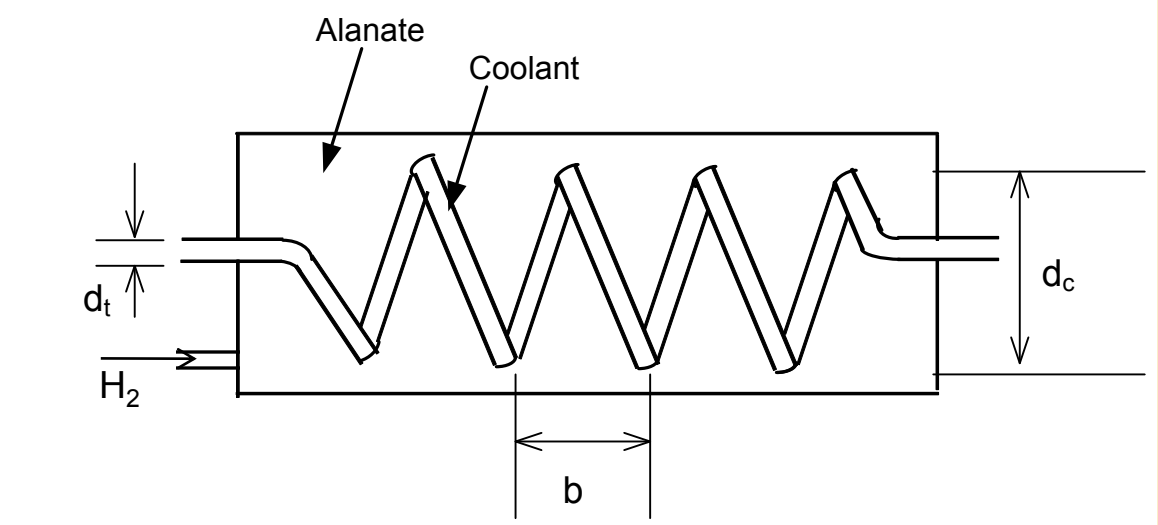
- Fins are essential to conduct the heat uniformly though out the bed
- Presence of fins reduce the characteristic penetration distance
- However the presence of fins add to the weight and volume of the heat exchanger significantly

Is there a way to get rid of the fins while ensuring good heat transfer within the bed ??

Helical Coil Heat Exchanger

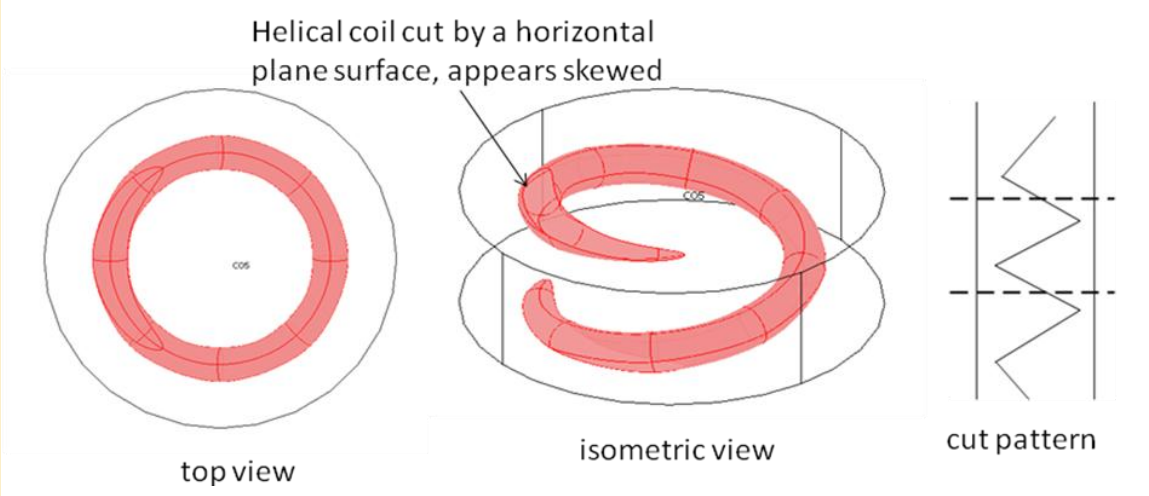
- For a given volume, the characteristic penetration distance is smaller for a helical geometry
- The use of fins can be avoided
- In addition, the heat transfer coefficient is roughly 2-3 times larger for flow through helical tubes compared to straight tubes

Schematic



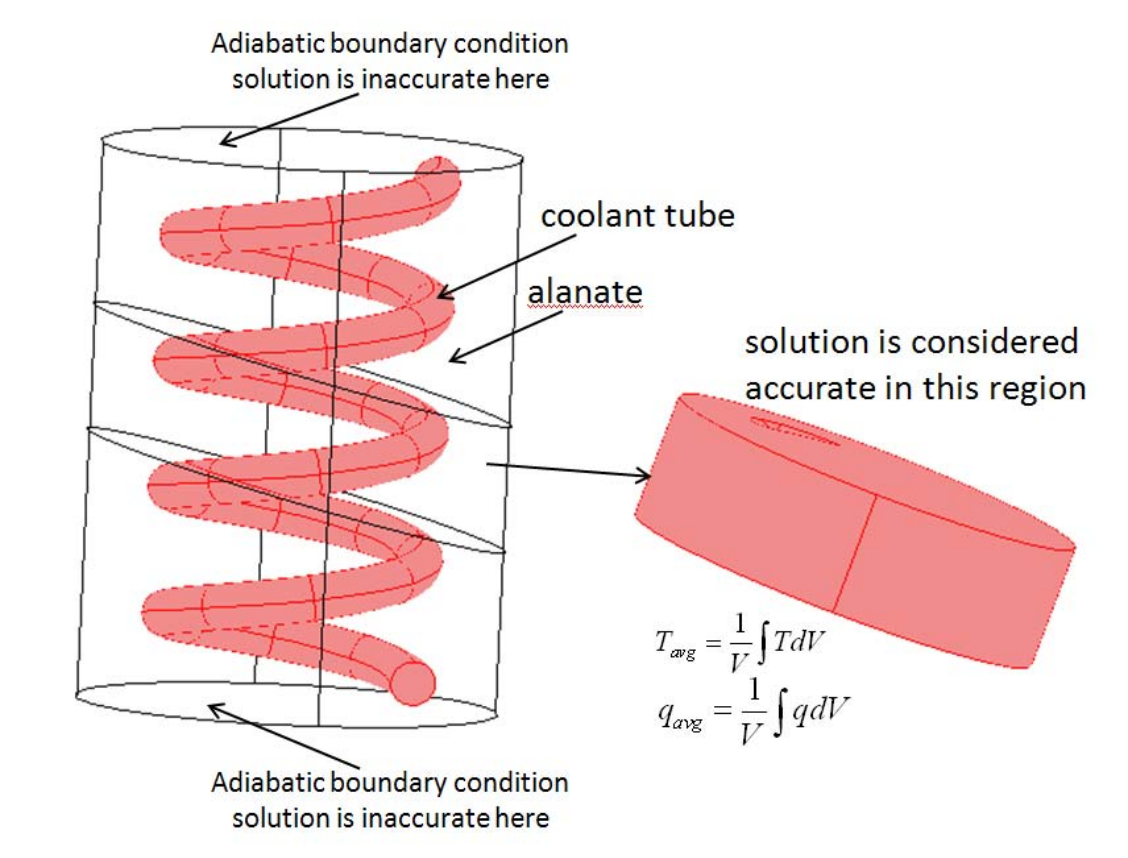
Model Complexities

Original idea was to take one ring and apply periodic boundary conditions



Meshing fails at the skewed surface

Modified Model



Nusselt Correlation

$$Nu = 0.0266\left[\frac{\mathrm{Re}^{0.85}}{\lambda^{0.15}} + 0.225\lambda^{1.55}\right]\mathrm{Pr}^{0.4}$$

λ is curvature ratio

Model Specifications

Table 1: Bed geometry and properties

Bed diameter (inner)	0.15 m
Cooling tube outer diameter (d_t)	0.016 m
Thickness of the tube	1 mm
Helical pitch	0.045 m
Helical radius	0.045 m
Bulk density	1000 kg/m^3
Porosity	0.48
Specific heat of alanate	1230 J/kg-K
Cooling fluid temperature	380 K
Cooling fluid flow rate	20 LPM
Bed pressure	Ramped up to 150 bar in 360 seconds
Effective thermal conductivity	8.5 W/m-K

Governing Equations

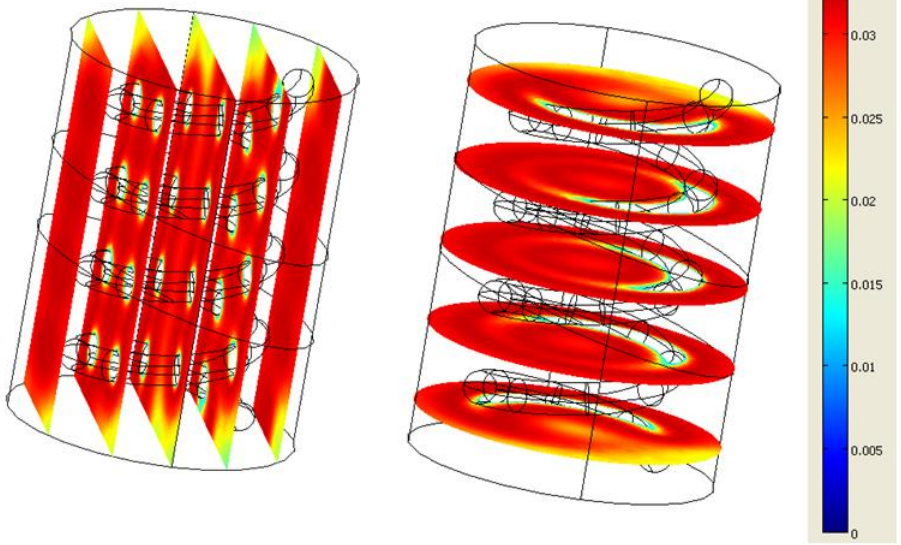
$$\underbrace{(1-\varepsilon)\rho_{ala}\left(c_p\right)_{ala}\frac{\partial T}{\partial t}}_{transient\ term}=\underbrace{\nabla.\left(k_{ala}\nabla T\right)}_{conduction\ term}+\underbrace{Q_a}_{heat\ absorption}-\underbrace{\varepsilon\rho_g\left(c_p\right)_g\frac{\partial T}{\partial t}}_{gas\ phase\ specific\ heat}$$

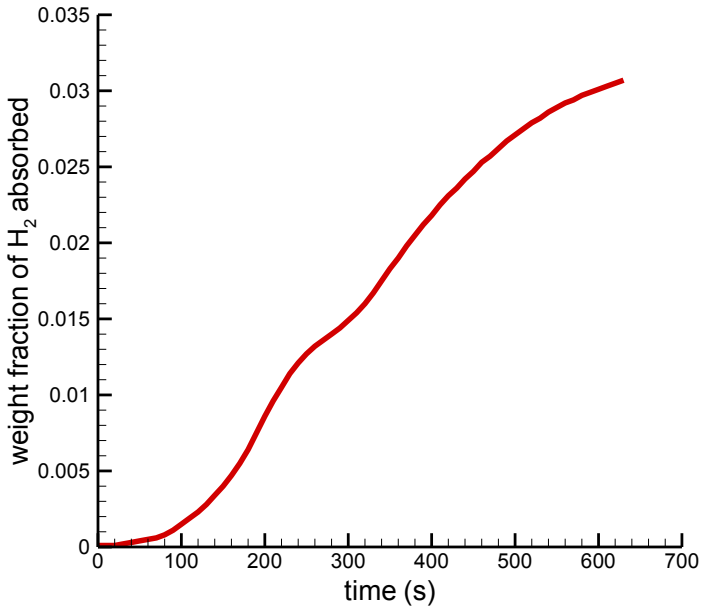
$$+\underbrace{\varepsilon\frac{\partial P_{bed}}{\partial t}}_{heat\ compression}\underbrace{-(1-\varepsilon)\rho_{ala}\left(c_p\right)_g q\frac{\partial T}{\partial t}}_{absorbent\ specific\ heat}$$

Boundary conditions at alanate-tube interface

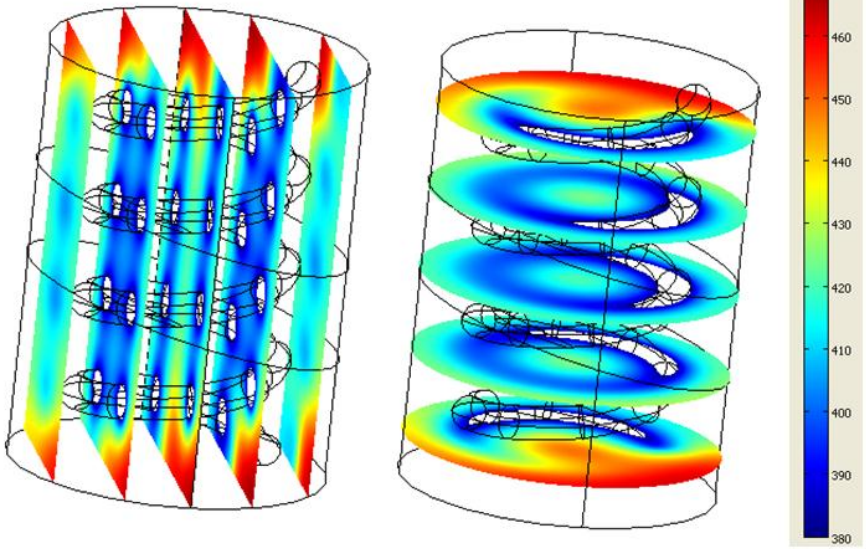
$$\vec{q}.\hat{n}=h_c A\left(T-T_f\right)$$

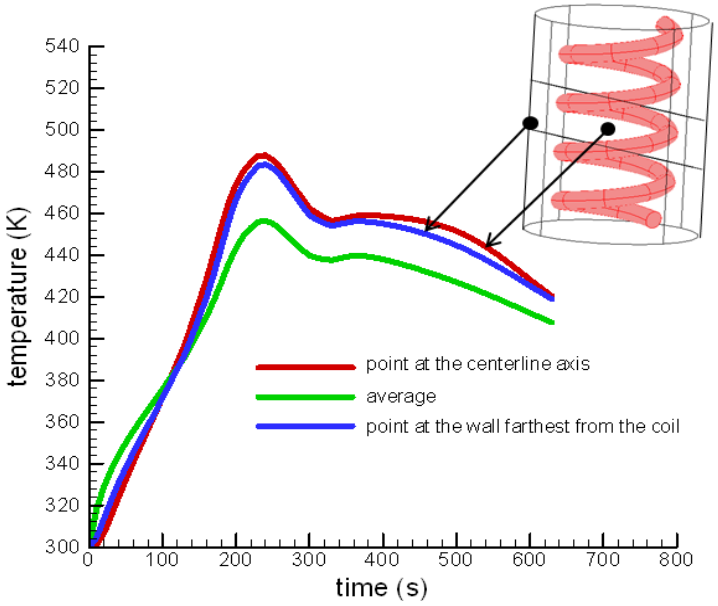
weight fraction contours



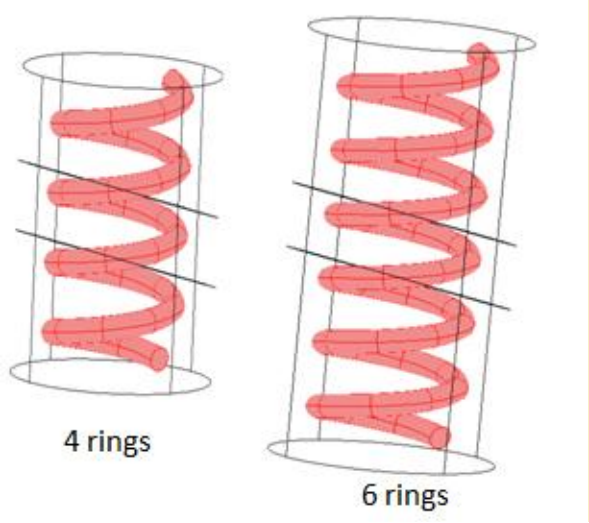


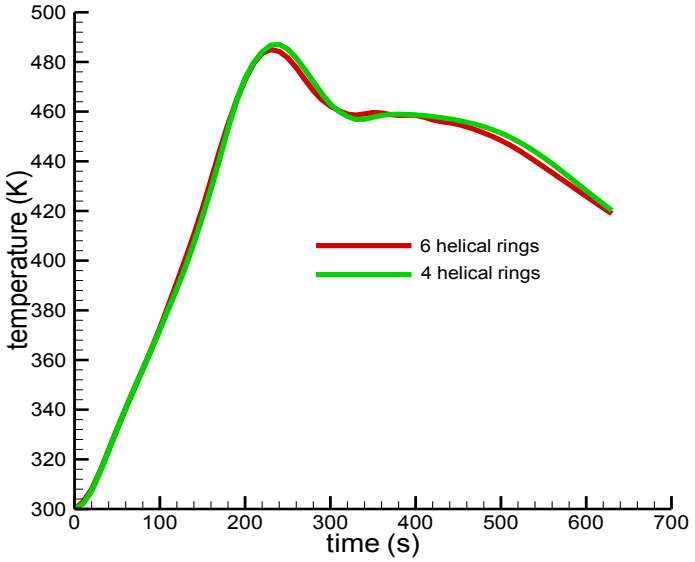
temperature contours (K)

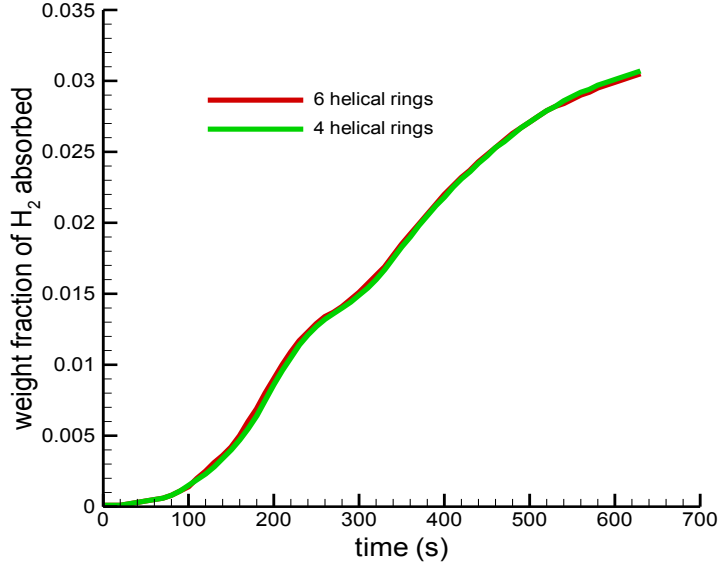




Geometric Consistency







Performance of different helical coil heat exchanger geometries

Aluminum tube thickness = 1 mm

	case-1	case-2	case-3	case-4	case-5	case-6	case-7	case-8
Shell radius (m)	0.075	0.08	0.088	0.01	0.075	0.075	0.075	0.07
Helical radius (m)	0.045	0.05	0.055	0.06	0.05	0.04	0.045	0.04
helical pitch (m)	0.045	0.05	0.055	0.06	0.045	0.045	0.05	0.04
Weight fraction of H_2 absorbed after 10.5 min	0.0307	0.0306	0.0287	0.025	0.03	0.0293	0.0307	0.03
Maximum temperature (k)	480	512	506	538	506	509	492	473
mass HEX (20 helical rings) (kg)	0.7285	0.8095	0.8904	0.9714	0.8076	0.6497	0.7306	0.6476
volume HEX (20 helical rings) (m^3)	1.151E-03	1.279E-03	1.407E-03	1.535E-03	1.276E-03	1.027E-03	1.155E-03	1.023E-03
mass of alanate (20 helical rings) (kg)	14.753	18.827	25.354	36.164	14.628	14.877	16.517	11.292
volume of alanate (20 helical rings) (m^3)	0.0148	0.0188	0.0254	0.0362	0.0146	0.0149	0.0165	0.0113
Aborbed hydrogen (20 helical rings) (kg)	0.4529	0.5761	0.7277	0.9041	0.4388	0.4359	0.5071	0.3387
weight of H2 stored per unit weight of bed*	0.0284	0.0285	0.0270	0.0238	0.0276	0.0273	0.0286	0.0276
weight of H2 stored per unit volume of bed*	28.478	28.653	27.191	23.982	27.593	27.409	28.694	27.507

* Includes only the alanate and the heat exchanger, the containment vessel is not included. Hydrogen in the gas phase is not included

Conclusions

- The heat exchanger mass is around 5% of the total bed mass. Previous design is 30% of the total mass
- Helical coil is a compact light weight heat exchanger.
- COMSOL 4.0 has more features to enable better post processing compared to COMSOL 3.5.
- Hopefully meshing issue would be better addressed in COMSOL 4.0

Questions??

Additional Slides

Stainless Steel tube thickness = 1.5 mm

	case-1	case-2	case-3	case-4	case-5	case-6	case-7	case-8
Shell radius (m)	0.075	0.08	0.088	0.1	0.075	0.075	0.075	0.07
Helical radius (m)	0.045	0.05	0.055	0.06	0.05	0.04	0.045	0.04
helical pitch (m)	0.045	0.05	0.055	0.06	0.045	0.045	0.05	0.04
Weight fraction of H_2 absorbed after 10.5 min	0.0307	0.0306	0.0287	0.025	0.03	0.0293	0.0307	0.03
Maximum temperature (k)	480	512	506	538	506	509	492	473
mass HEX (20 helical rings) (kg)	3.1406	3.4895	3.8385	4.1874	3.4813	2.8008	3.1497	2.7920
volume HEX (20 helical rings) (m^3)	1.151E-03	1.279E-03	1.407E-03	1.276E-03	1.027E-03	1.155E-03	1.027E-03	1.023E-03
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volume of alanate (20 helical rings) (m^3)	0.0148	0.0188	0.0254	0.0362	0.0146	0.0149	0.0165	0.0113
Absorbed hydrogen (20 helical rings) (kg)	0.4529	0.5761	0.7277	0.9041	0.4388	0.4359	0.5071	0.3387
weight of H2 stored per unit weight of bed*	0.0247	0.0252	0.0243	0.0219	0.0237	0.0241	0.0251	0.0235
weight of H2 stored per unit volume of bed*	28.478	28.653	27.191	23.982	27.593	27.409	28.694	27.507
* Includes only the alanate and the heat exchanger, the containment vessel is not included. Hydrogen in the gas phase is not included								