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Thermophysical property measurements and thermal energy storage capacity analysis of aluminum alloys

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ABSTRACT

Ten aluminum alloy samples are prepared using a casting method by carefully designing compositions of Al-Si, Al-Cu, Al-Mg, and Al-Cu-Zn alloys. This paper measures the phase change temperature, latent heat, and specific heat of the samples using a differential scanning calorimeter (DSC), the thermal diffusivity using a laser flash method, and derives the thermal conductivity of each sample. The effects of element addition and temperature on the performance of the aluminum alloy phase change materials (PCM) are comprehensively analyzed. The thermal energy storage (TES) capacities of the samples in different temperature ranges are also analyzed. The results show that adding Cu, Zn, and Si to an aluminum alloy helps reduce the melting point of the alloy. The addition of dense elements such as Cu and Zn in aluminum alloys improves the alloy's TES capacity per volume unit. Based on experimental results, this paper also recommends fitting formulas for calculating the temperature dependent specific heat and thermal conductivity of the aluminum alloys studied.

1. Introduction

High temperature thermal energy storage (TES) is very important for the effective use of solar energy. It is a critical component of concentrated solar power (CSP) generation unit. An effective TES system can improve the thermal management level of a CSP unit, and ensure safe operation of the system under load during cloudy days or at night instead of shutting down due to loss of sunlight. Moreover, an efficient TES system is critical for upsizing a CSP generation unit and for improving system global efficiency by increasing the load capacity (Medrano et al., 2010; Kenisarin, 2010). Therefore, it is necessary to develop a safe and economic high temperature TES system for CSP generation unit.

There are primarily three TES methods that can be used with CSP systems, namely sensible, latent, and thermochemical systems. Latent TES is current one of the most in-depth investigated methods. It can achieve TES at near constant temperature and the TES capacity of the latent method at unit volume is 5–14 times larger than with sensible TES methods (such as water, refractory brick or rock, etc.). These advantages also allow the application of latent TES in many other energy saving fields. Thus, many researchers have given considerable attention to latent TES in recent years (Kenisarin, 2010; Gil et al., 2010; Agyenim et al., 2010; Liu et al., 2012; Cheng et al., 2010a).

The phase change material is undoubtedly the key factor in determining the performance of a latent TES system. A large number of materials can experience a phase change at a specific temperature. High temperature molten salts and metal alloys are currently considered two of the most understood potential phase change materials (Kenisarin, 2010; Gil et al., 2010; Agyenim et al., 2010; Liu et al., 2012; Cheng et al., 2010a). Many salt materials can store latent heat at high densities and high temperature but have a low thermal conductivity, which is a significant obstacle to heat accumulation and release rates (Michels and Pitz-Paal, 2007; Steinmann and Tamme, 2008; Dunn et al., 2012; Relloso and Delgado, 2009). Therefore, much effort has been devoted to improve the thermal conductivity of salt PCMs by utilizing a fin tube configuration, adding metal materials, etc. (Fan and Khodadadi, 2011; Liu et al., 2005; Zhao and Wu, 2011; Zhou and Zhao, 2011; Wang et al., 2015; Wu and Zhao, 2011; Do Couto Aktay et al., 2008; Ermis et al., 2007; Shabgard et al., 2010; Pincemin et al., 2008; Acem et al., 2010; Shin and Banerjee, 2011), which, however, as indicted by Wang et al. (2015), lead to significant weight and cost increasing. Liquid–solid separation and large changes in volume when melting are other issues that must be addressed when using salt as the TES medium (Kenisarin, 2010; Gil et al., 2010; Agyenim et al., 2010; Wu and

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Zhao, 2011; Do Couto Aktay et al., 2008; Ermis et al., 2007; Shabgard et al., 2010; Pincemin et al., 2008; Acem et al., 2010; Shin and Banerjee, 2011).

Many metal alloys (primarily aluminum alloys) can also store latent heat with favorable cycling stability, the thermal conductivity of metal alloys is dozens to hundreds times higher than most salts (Kenisarin, 2010; Gil et al., 2010; Agyenim et al., 2010; Liu et al., 2012; Cheng et al., 2010a), Several studies have been reported on the thermophysical properties of different metals and alloys as PCMs (Kenisarin, 2010; Shin and Banerjee, 2011). It was reported that the large latent heat on a mass or volume basis were obtained in binary and ternary alloys with abundant elements Al, Cu, Mg, Si, and Zn (Shin and Banerjee, 2011; Sun and Zhang, 2005; Achard, 1981; Gasanaliev and Gamataeva, 2000; Sun et al., 2007; Zhang et al., 2012; Birchenall and Telkes, 1976; Birehenall and Riechman, 1980; Farkas and Birehenall, 1985; Cherneeva et al., 1982; Cheng et al., 2010b; Huang et al., 1991; Wang et al., 2006; Fukahori et al., 2016; Akiyama et al., 1992). Table 1 gives a summarization of the thermophysical properties of some aluminum alloys. The use of metal alloys with high thermal conductivity as TES materials it still require an extensive work related to design and preparation of new eutectic metal alloys with specific melting temperatures and determination of thermophysical properties is required.

Birchenall and Telkes (1976) first analyzed the possibility of storing thermal energy by using latent heat in metals. Birehenall and Riechman (1980) subsequently measured the melting temperature and heat of fusion using a differential scanning calorimeter (DSC) and differential thermal analysis (DTA). The melting temperature and heat fusion of some new metal eutectic alloys were also measured by Farkas and Birehenall (1985). Achard (1981) undertook a TES study of aluminum-magnesium alloys. Gasanaliev and Gamataeva (2000) and Cherneeva et al. (1982) analyzed the TES properties of various melts, as well as studying the use of metal alloys for heat accumulation. Wang et al. (2006) measured $AlSi_{12}$ and $AlSi_{20}$ alloys using DSC. Fukahori et al. (2016) given thermal analysis of Al-Si alloys as high-temperature PCM and their corrosion properties with ceramic material, while Sun et al. (2007) tested the thermal reliability of Al(60 wt.%)–34 Mg–6Zn through 1000 cycles in a DSC analysis. Cheng et al., 2010a,b analyzed the effect of adding different elements on the phase change temperature and latent heat of aluminum alloys. Akiyama et al. (1992) analyzed the thermal performance of spherical capsules containing six phase change materials (PCM). The group showed that metallic PCMs are more advantageous for obtaining constant temperature heat transfer fluids due to their higher thermal conductivity. Blanco-Rodríguez et al. (2014), Rodriguez-Aseguinolaza et al. (2014) given a thermophysical and Thermodynamic study on the eutectic Mg49–Zn51 alloy for TES application, Risueño et al. (2015) given a study on Mg-Zn-Al eutectic alloys as PCM. Zhang et al., (2014), Fukahori et al. (2016), and Nomura et al. (2015) give an encapsulation study on some metal alloys by adopting different methods. Blanco-Rodríguez et al. (2015) and Kotzé et al. (2014) give a study on TES heat exchangers by adopting Al-12Si alloy and Mg-51%Zn as PCMs. Kenisarin (2010), Liu et al. (2012), Zhang et al. (2012) also give a summarization on the thermophysical properties of some metal alloys in their studies.

While certain investigations have shed light on the topic, knowledge of the thermophysical properties of aluminum alloys in the literature, as mentioned by Kenisarin (2010), Zhang et al.

Table 1
A summary of thermophysical properties of some aluminum alloys.

Content (wt.%)	Phase change temperature (°C)	Density (kg/m³)	Latent heat in unit mass (kJ/kg)	Latent heat in unit volume (MJ/m³)	Specific heat (kJ/(kg K))		Thermal conductivity (W/(m K))		References
					Solid	Liquid	Solid	Liquid	
34 Mg	450	2300	310	713	1.73	–	80	50	Cheng et al. (2010a)
8Si	576	–	428.9	–	1.058	–	–	–	Huang et al. (1991)
12Si	576	2700	560	1512	1.038	1.741	160	–	Wang et al. (2006)
12Si	572	–	441	–	–	–	–	–	Fukahori et al. (2016)
12.2Si	580	2620	499.2	1307	1.036		165		Wang et al. (2015)
12.5Si	577	2250	515	1160	1.49	–	180	70	Cheng et al. (2010a)
12.6Si	576	–	463.4	–	1.037	1.741	–	–	Huang et al. (1991)
20Si	576	–	528.4	–	0.970	–	–	–	Huang et al. (1991)
20Si	580	2580	552.6	1426	0.984	–	158	–	Wang et al. (2015)
20Si	585	–	460	–	–	–	–	–	Wang et al. (2006)
23.4Si	575	–	395	–	–	–	–	–	Fukahori et al. (2016)
25Si	577	–	432	–	–	–	167	–	Fukahori et al. (2016)
30Si	580	2540	644.3		0.896	–	140	–	Wang et al. (2015)
40Si	580	2510	721.2		0.879	–	110	–	Wang et al. (2015)
96Zn	381	6630	138	916	–	–	–	–	Gasanaliev and Gamataeva (2000)
33.2Cu	548	3424	351	1200	1.11	–	130	80	Cheng et al. (2010a)
Si/Fe	577	2600	515	1339	0.939	1.17	180	–	Zhang (2009)
40Si/15Fe	869.4	3360	562.2	1889	0.762	–	12.8	–	Wang et al. (2015)
53Si/30Ni	1079.2	4290	960.3	4120	0.653	–	51.7	–	Wang et al. (2015)
34Cu/1.7Sb	545	4000	331	1324	–	–	–	–	Gasanaliev and Gamataeva (2000)
13Cu/15Zn	493.3–598	3420	158.3	538.8	–	–	–	–	Cheng et al. (2010b)
5.25Si/ 27Cu	520	–	365.8		0.875	1.438	–	–	Huang et al. (1991)
5Si/ 30Cu	571	2730	422	1150	1.30	1.20	–	–	Cheng et al. (2010a)
13.2Si,/5Mg	552	–	533.1	–	1.123	1.249	–	–	Huang et al. (1991)
34Mg/6.42Zn	447–450	2393	329–316	781–756	1.049	1.426	–	–	Sun et al. (2007)
35Mg/6Zn	443	2380	310	740	1.63	1.46	–	–	Cheng et al. (2010a)
22Cu/18Mg/6Zn	520	3140	305	960	1.51	1.13	–	–	Kenisarin, (2010)
24.5Cu/12Mg/18Zn	460–624	380 0	315.3	1 197.3	–	–	–	–	Cheng et al. (2010b)
26Cu/5Mg/20.5Zn	458–488.3	386 0	163.8	632.3	–	–	–	–	Cheng et al. (2010b)
5.2Si/28Cu/2.2Mg	507	440 0	374	1664	–	–	–	–	Gasanaliev and Gamataeva (2000)