Applied Thermal Engineering 236 (2024) 121371

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Medium temperature heat pipes – Applications, challenges and future direction

Thomas C. Werner [a,*], Yuying Yan [b,*], Tassos Karayiannis [c], Volker Pickert [a], Rafal Wrobel [a], Richard Law [a]

[a] School of Engineering, Newcastle University, Newcastle, UK
[b] Department of Fluids and Thermal Engineering, University of Nottingham, Nottingham, UK
[c] Department of Mechanical and Aerospace Engineering, Brunel University, London, UK

ARTICLE INFO

Keywords:
Heat pipe
Thermal management
Heat transfer
Medium temperature fluids
Two-phase heat transfer

ABSTRACT

Heat pipes have played a large part in the thermal management market for the past five decades and have contributed to the development and optimisation of countless components in a wide range of high-level applications, most notably in the aerospace, electronics, automotive and power generation industries. These thermal management systems span a wide range of temperatures, which in turn requires the heat pipe fluid and casing material to be specially selected to meet the application requirements. Recently, there has been an increasing demand for heat pipes which can operate in the 300–600 °C temperature range – a range which is still underdeveloped in the heat pipe marketplace due to the lack of conventional fluids which can adequately operate at these temperatures. This range is referred to as the 'medium' or 'intermediate' temperature range. The analysis and exploration of novel fluids, which could potentially be used in this range, will cater for a huge market potential. Although there has been mild development in this temperature range with the aim of testing particular fluid/metal combinations which may be suitable, there appears to currently be a severe lack of continuity in the work with little progression towards a definitive solution and no central reference catalogue of successful and unsuccessful tests. Previous works on the topic tends to follow a 'patchwork' process, often with overlaps in testing and with a focus only on long-term compatibility tests with a limited analytical approach which often lead to incompatible results. This paper intends to summarise all major and stand out efforts in developing medium temperature heat pipes and highlight the most promising fluids and wall materials which have been tested to date. To summarise the content, this review will explore (a) current applications which could benefit from the use of medium temperature heat pipes, (b) the work that has been done on investigating medium temperature fluids, (c) highlight some of the principles behind heat pipe performance prediction, fluid analysis, fluid/metal compatibility and fluid selection and (d) suggest the potential future direction of research in this area, particularly focusing on the development of novel heat pipe fluids. Additionally, a standardised fluid assessment framework is also proposed aiming to aid the identification and analysis of both existing and newly developed heat pipe fluids.

1. Introduction

Thermal management forms a fundamental part of most modern engineering products and industries. In the current technological landscape, heat regulation is a vital aspect of the ever-increasing power densities of modern engineering components. To advance, enhance, optimise, and innovate component designs, the ability to dissipate heat at high rates is vital. In this respect, the heat pipe has had a high interest in many modern applications due to its superior heat transfer qualities such as its ability to passively transfer heat at equivalent conductivities far beyond any conventional solid material in addition to being both compact, lightweight and able to be formed into eccentric shapes. The heat pipe can in some cases even completely replace actively pumped

Abbreviations: CPU, Central Processing Unit; CSP, Concentrated Solar Plant; EMF, Electromotive Force; HEXAG, Heat Exchanger Action Group; LFR, Linear Fresnel Reflector; MSD, Material Safety Datasheet; NCG, Non-Condensable Gas; PDC, Power Dish Collector; PFC, Plasma Facing Component; PTC, Parabolic Trough Collector; RRK, Rice, Ramsper and Kassel; SPT, Solar Power Tower.

* Corresponding authors.
E-mail addresses: tom.werner@ncl.ac.uk (T.C. Werner), yuying.yan@nottingham.ac.uk (Y. Yan).

https://doi.org/10.1016/j.applthermaleng.2023.121371
Received 2 January 2023; Received in revised form 13 July 2023; Accepted 14 August 2023
Available online 19 August 2023

Nomenclature

A	Bond vibration frequency OR Concentration of element
A_0	Solubillity of the element in soltion
A_v	Vapour area
A_w	Wick cross sectional area
c_p	Specific heat capacity
d	Wire diameter
d_e	Equivallent diameter
d_i	Internal diameter
d_o	Heat pipe outer diameter
d_v	Vapour space diameter
E^+	Activation energy
E^0	Base electromotive force
F	Faraday constant
f	Friction factor
g	Acceleration due to gravity
h_{fg}	Enthalpy of vapourisation
h_m	Mass transfer coefficient
J	Mass flux
K	Permeability
k_l	Liquid thermal conductivity
k_s	Solid thermal conductivity
k_w	Equivallent wick thermal conductivity
k_{wall}	Thermal conductivity of wall material
l	Heat pipe length
l_a	Adiabatic length
l_c	Condenser length
l_e	Evaporator length
l_{eff}	Effective length
$\dot{m}$	Mass flow rate
M	Liquid mass transport factor
M_a	Representative puremetal
M_b	Representative hlide metal
n	Number of electrons
N	Mesh count
P_i	Internal pressure
P_o	External/Reference pressure
P_v	Vapour pressure
Pr	Prandtl Number
$\Delta P_{c,max}$	Maximum Capilliary pressure drop
ΔP_c	Capilliary pressure drop
ΔP_g	Gravitational pressure drop
ΔP_l	Liquid phase pressure drop
ΔP_v	Vapour phase pressure drop
Q	Heat input
Q_{cap}	Maximum capilliary heat input
q_{cr}	Critical heat flux
Q_{ent}	Entrainment heat input limit
Q_{sonic}	Sonic heat input limit
Q_{visc}	Viscous heat input limit
r_c	Capilliary radius
r_{eff}	Effective radius
r_i	Internal radius
r_n	Nucleation radius
r_v	Vapour space radius
R	Gas constant
R_1	First order rate constant
Re	Reynolds number
Re_r	Radial Reynolds number
Re_v	Vapour Reynolyds number
t	Thickness
T	Temperature
T_v	Vapour temperature
t_{wall}	Wall thinckness
t_{wick}	Wick thickness
u_v	Vapour velocity
X_{cp}	Representative halogen product
α_t	Thermal expansion correction factor
θ	Heat pipe inclination angle
θ^*	Contact angle, Degree
δ_{an}	Annular width
ε	Porosity
μ_l	Liquid viscosity
μ_v	Vapour viscosity
ρ_l	Liquid density
ρ_v	Vapour density
σ	Surface tension of fluid
σ_h	Ultimate tensile strength

cooling systems diminishing the system complexity and potential for failure while maintaining an equivalent rate of cooling, particularly when implementing technologies such as the 'loop' heat pipe [1,2].

Heat pipes have had a vital contribution to thermal management systems in a wide range of industries such as aerospace, electronics, automotive and power generation. Some examples of applications which have benefited from heat pipes include aviation part cooling, communication systems thermal management, CPU cooling, high power electronics cooling, power station heat recovery, satellite and spaceship thermal management, formula racing, waste heat recovery and solar thermal energy conversion [2–23]. Their impact has particularly accelerated the development of space-bound instruments/vehicles and consumer electronic devices while, in turn, many researchers in these fields have provided valuable contributions to heat pipe theory and development [21,24–27]. Fig. 1 shows the increasing trend in heat pipe related publications over the years since Gaugler first introduced the concept of a heat pipe in a patent under the title 'Heat transfer device' [28]. Since then, there has been a rapidly increasing interest in heat pipe related research with the vast majority of research originating in China and the USA, see Fig. 2.

From this, heat pipes were developed for use in every temperature range spanning cryogenic to exceptionally high temperature applications. Over this time, however, the development of heat pipes in a particular temperature range has proven to be challenging due to the lack of 'conventional' fluids which are able to operate within it. This is referred to as the 'medium temperature range', which loosely spans 300–600 °C. This range is dictated though the maximum working temperature of water heat pipes (generally in the region of 300–350 °C) [30] to the minimum working temperature of conventionally used liquid metals such as Sodium, Lithium and Potassium (with Sodium reaching the lowest operating temperature of 650 °C) [31]. Within the medium temperature range, there is a limited choice of fluids which can be used to cover this gap, and the commonly known fluids which are theoretically able, such as Mercury and Caesium, are met with extreme practical difficulties relating to wick wetting, compatibility with wall metals, toxicity, vapour ignition, high development cost and difficulties in qualifying such devices in highly regulated industries (e.g. aerospace and nuclear) [32]. Though there have been many studies which have identified alternative potential fluids which could theoretically work within the temperature range [30–48] there has still been no definitive and widely commercially viable solution to date. Recently a review paper which is derived from Werner's HEXAG presentation [46] exploring the challenges with medium temperature heat pipe fluid investigations and Werner's EngD Thesis [47] exploring the analysis and

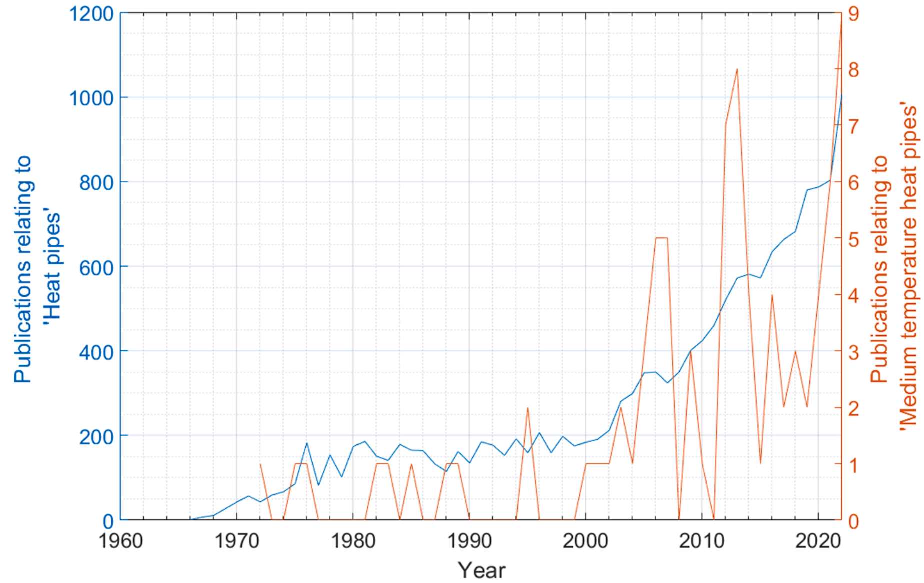

Fig. 1. Papers published directly relating to heat pipes. Produced using data from Scopus.com [29].

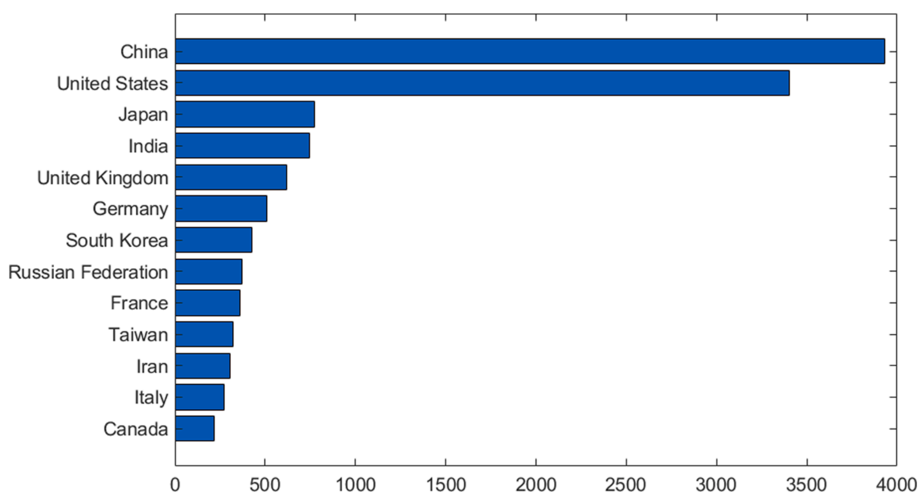

Fig. 2. Share of top 13 countries contributing to heat pipe research data presented in Fig. 1 for years 1960–2022. Produced using data from Scopus.com [29].

development of intermediate temperature heat pipes has reported the challenges of the use of intermediate temperature fluids in the context of loop heat pipes [48]. With the existing fluids, there appears to be a trade-off between ideal thermal characteristics and chemical stability. A review of current work which has been done in the medium temperature range and identification and analysis of key medium temperature fluids is presented here. Additionally, areas which could be further explored in terms of working fluid analysis and testing are highlighted.

The renewed interest in pursuing the optimisation of heat pipes within the medium temperature range stems from the increased need for thermal management for applications such as waste heat recovery [49], high power electronics cooling [7,50], fuel cell thermal management [51], nuclear power thermal management [39,52],concentrated solar conversion [53–55] and thermal storage [56]. Hence, the development of effective heat pipes within the medium temperature range is of great interest to organisations currently working in the thermal management field. Fig. 1 shows the number of papers over the years which directly refer to heat pipes operating in the medium temperature range. Here it can be seen that there is quite a sporadic research output in this area, but which is nevertheless following a generally increasing trend since the turn of the millennia (though still currently remaining in single figures per annum). Fig. 3 reveals the share of topics which are associated with papers relating to medium temperature heat pipes. Interestingly it can be seen that the solar power generation market currently dominates the research field with 48% of medium temperature heat pipe papers directed towards this technology. Pure fluid/metal research with no specific application contributes 23%, and Aerospace applications then follow with 8% of medium temperature heat pipe research output linked to the field. Of course, this data is reflective only of publicly available research, while there certainly will be many other privately driven investigations into the technology which are not reported here.

For a wider scope of the heat pipe market Jose et al. [22] gives an extensive review of the various types of heat pipes currently available outside of the medium temperature range and their application in a wide range of fields including nuclear, geothermal, waste heat recovery, space systems, electric vehicle thermal management, solar thermal systems, and electronics cooling.

2. Current and emerging medium temperature heat pipe applications

The enhanced thermal conductivity offered by a heat pipe in the medium temperature range could benefit a variety of applications. Fig. 3 highlights the applications which are currently providing the main

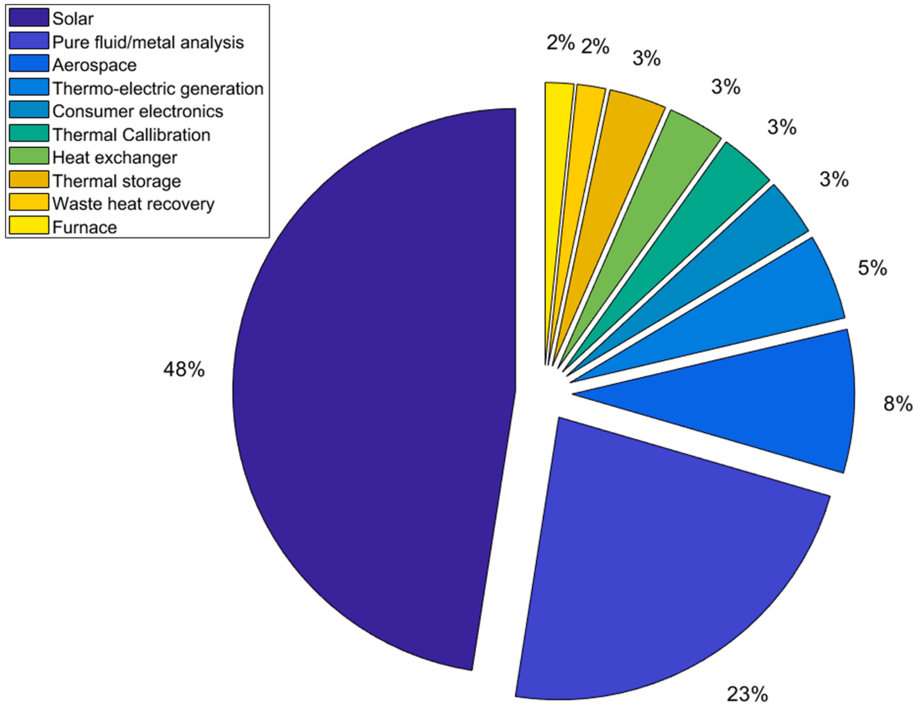

Fig. 3. Share of subjects linked to the exploration of medium temperature heat pipes taken from 70 papers on the topic spanning 1972 to 2022. Produced using data from Scopus.com [29].

impetus for medium temperature range heat pipe development. Some of the current developments in key markets such as high-power electronics, concentrated photovoltaics, nuclear fission/fusion and industrial waste heat recovery have a strong potential to benefit from the use of medium temperature heat pipes and will be highlighted in this section.

2.1. Renewables market

The renewables market is currently the dominant sector in the development of medium temperature heat pipes. Many applications involving concentrated solar loads have components which operate within the medium temperature range. The high thermal conductivity offered by the heat pipe can help maintain components at the desired operating temperature during high heat loads, maintain more isothermal surfaces over a heat cycle, and increase the overall thermal efficiency of the system.

As detailed by Merchán et al. [57], many concentrated solar power (CSP) plants currently operate at peak cycle temperatures of ~480–550 °C such as the Archimede plant in Italy, Ivanpah plant in the US and Dancheng plant in China (see Table 1). It is reported that the receiver outlet temperatures in these plants can reach up to 565 °C. The use of medium temperature heat pipes could bring benefit to a plethora of components within these systems to increase both cycle and conversion efficiencies. Within the collectors, spreading the concentrated heat over a larger area could help to reduce the pumping power needed across the heat exchanger, create more isothermal component surfaces, and allow for more versatile collector module designs as demonstrated in lower temperature ranges by Jouhara et al. [27] and Senthil et al. [58], Aramesh et al. [59], Chibule et al. [60], Xu et al. [61] and Kumar et al. [62]. Heat pipes could also be used to more effectively transfer heat in peripheral thermal energy storage devices, with the additional benefit of passive bi-directional capability. Senthil et al. [58] details the application of heat pipes in a wide range of primary and peripheral equipment including the integration of bi-directional heat pipe based energy storage systems. Wang et al [63] also demonstrates a latent heat storage unit using micro heat pipe arrays where the charging and discharging occurs along the centre of the heat pipe.

Direct thermal to electrical conversion is another popular development in the renewables market. Advancements on Stirling engine conversion applications such as electrical conversion for thermal chemical storage currently being developed by companies such as Texel [64,65] and Mahle [66], could also potentially benefit from the development of

Table 1
Specifications for main large-scale concentrated solar power plants Produced using data from He et al. [67]. Third generation plants are exploring the use of silica sand, calcinated flint clay and ceramic particles as well as a range of chlorinated or carbonated molten salts as heat absorbing mediums within the medium temperature range.

Receiver outlet temperature (°C)	Gen 1	Gen 2		Gen 3
	250–450	500–565	720	>700
Technology type(s)	PTC, SPT, LFR	PTC, SPT, LFR	PDC	Molten Salts, Gas or Particle
Plats	SEGS I, Sierra, eLLO	Archimede, Ivanpah, Dacheng	Maricopa	N/A
Cycle type	Steam Rankine Cycle		Stirling	Brayton Cycle
Heat transfer medium	Oil or Steam	Steam or Molten Salt	Gas	Molten Salt, Gas or Particle
Incorporation of thermal energy storage	Early designs: no Mature designs: yes	Early designs: no Mature designs: yes	No	Yes
Cycle efficiency (%)	28–38	38–44	38	>50
Peak cycle temperature (°C)	240–440	480–550	720	>700
Solar-electric efficiency (%, av. annual)	9–16	10–20	25	25–30

medium temperature heat pipes in both the energy storage and Stirling engine conversion technology. Commercial solar Stirling engines can be designed to operate at a variety of temperatures. Singh et al. reported a maximum thermal efficiency of 32% for a design with an absorber temperature of 577 °C [54]. Medium temperature heat pipes in these systems could vastly increase the heat transfer performance between the absorber and Stirling converter head allowing for highly effective passive heat transfer between them with minimal temperature drop and thermal lag.

2.2. Waste heat recovery market

According to estimates by Forman et al. [68] high temperature waste heat (i.e. those above 300 °C) comprises 21% of total global heat recovery potential in the energy services market. When calculating the waste heat distribution in 2012, this equates to roughly 50.7 PJ of wasted energy [68]. The principal source of waste heat at high temperatures are form exhaust/effluence streams in the transportation, industrial and commercial markets. The energy services market is the next largest contributor.

In these energy intensive industrial processes, the main components which experience high temperatures are the waste heat boilers, recuperators, regenerators and plate heat exchangers. The use of medium temperature heat pipes could aid the development of both the components themselves and the next generation recovery technologies, such as rotating drums, solid slag impingement, mechanical stirring, thermal storage, and thermionic generators [49]. Vizitu et al. [69] demonstrates a heat pipe heat exchanger system used to extract heat from exhaust flue. Priya et al. [70] developed a convergent truncated cone thermosyphon for use in heat recovery systems. Jouhara et al. [71,72] has developed a heat pipe heat exchanger systems for heat recovery in the aluminium die casting and ceramics industries.

Waste heat boilers traditionally consist of several water tubes placed inside the medium/high temperature flue streams which convert the water into steam for either power generation or pre-heating [49]. In these systems, the use of medium temperature heat pipes could allow for more compact designs with more isothermal heating surfaces in the water stream with potentially lower component pressure drops. Heat pipe systems could also be designed to better couple the waste heat boiler with afterburners, preheaters and fin-tubed evaporators as demonstrated by Yodrak et al. [73] with a heat pipe-based air pre-heater for an industrial furnace.

2.3. Nuclear market

Another industry showing great potential for applications requiring medium temperature heat pipe development is the nuclear power industry. The diverter target plates for nuclear fusion reactors have expected plasma facing components (PFC) with operation temperatures ranging between 300 °C and 600 °C [74]. Fig. 4 shows and example of brazed W/Cu composite diverter target plates which currently use either helium or water as the cooling medium. Use of heat pipes in these structures could help to reduce hot spot temperatures by spreading the incident heat over a larger area, which in turn would also provide a larger cooling surface as well as lower the overall heat flux density to the coolant.

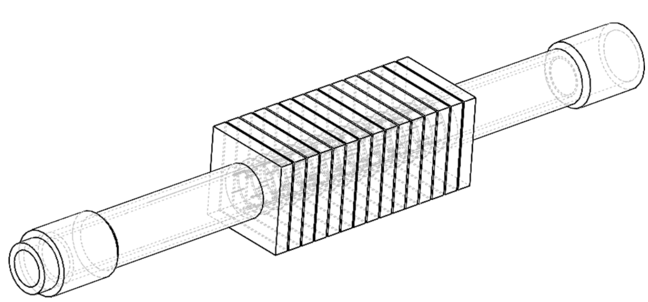

Fig. 4. Diverter target plate structure. A re-creation of images from You et al. [74].

Yan et al. [75] overviews the development of micro heat pipe cooled reactors which utilises a monolithic structure to transfer heat from the reactor core to a heat conversion unit such as a closed Brayton, Rankine or Stirling cycle engines, or alternatively, thermionic or magnetohydrodynamic power conversion technology. Li et al. [52] demonstrated the development of a Mercury heat pipe for a medium temperature heat pipe cooled reactor. Zohuri et al. [76] reviews the use of medium temperature heat pipe heat exchangers for molten slat cooled reactors suggesting Potassium, Sodium or Lithium to be used for salt temperature between 500 °C and 700 °C.

2.4. Other markets

In addition to the previously mentioned markets, some promising new engineering developments could most certainly benefit from the use of heat pipes in the medium temperature range. In the space and aviation industry there are a variety of sub-system components which operate in the medium temperature range. When operating vehicles at hypersonic speed, for instance, there is a great need for thermal management of the outer surfaces of the aircraft [9]. Here, medium temperature heat pipes could be used to spread the heat over the wing surface, reducing the leading-edge temperature and providing a greater area to extract heat. Coutinho et al. [77] details several applications of heat pipes for hybrid-electric aircraft development. Fusaro et al. [78] demonstrates the use of liquid metal heat pipes to enhance heat transfer from small air passages in the leading edge of the STRATOFLY MR3 hypersonic vehicle as seen in Fig. 5.

Another use in the medium temperature range is in the thermal management of engine walls. Simulations by Changbao et. al. [8] show that the exit wall temperature for hydrogen fuel engines in hypersonic vehicles is 600 °C with a heat load of 100–800 kW. The integration of heat pipes in an active cooling loop for these engines could vastly enhance the cooling capacity and decrease the overall energy needed for cooling. Other potential technologies which could benefit from medium temperature heat pipes include thermo-acoustic energy converters, turbine engine housing components, high temperature battery thermal storage and synthetic diamond manufacture instruments amongst many others.

3. The challenges with medium temperature heat pipes and summary of research to date

Medium temperature heat pipes have often been investigated together with high temperature heat pipes. Initial research tended to

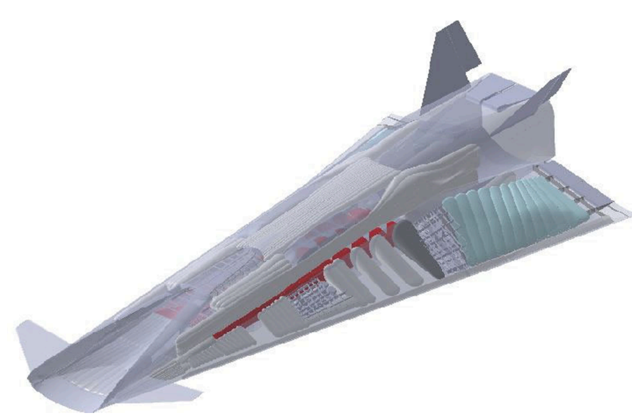

Fig. 5. STRATFLY MR3 Hypersonic vehicle concept by Fusaro et al. [78].

focus on alkali metals such as Caesium, Rubidium and Potassium. However, it was noted that when operating these working fluids within the medium temperature range, the vapour pressures and density were excessively low, causing sonic vapour velocities within the pipe, which in turn leads to choking. These effects can be mitigated by using larger vapour spaces, however, the required diameter for the use of these metals became so large as to be impractical in many common heat pipe applications [79].

When assessing the heat pipe functionality, consideration must be taken into assessing the three main failure modes which can take place. These are; thermal degradation of the fluid leading to non-condensable gas (NCG) generation, chemical reaction of the fluid with the wall material leading to NCG/particulate generation and structural failure of the wall material due to excessive vapour pressure or thermal/mechanical fatigue. The type of non-condensable gas generated is typically dependent on the fluid and metal in question as well as the type of failure. The most common non-condensable gases generated are; formation of carbon monoxide/dioxide and various alkanes when utilising organic fluids, formation of hydrogen when utilising hydrogen baring non-organic compounds such as water, and ingress of air (nitrogen, carbon dioxide, argon and oxygen) when structural failure or production errors are present. The NCG's tend to accumulate at the 'low' pressure end of the heat pipe (i.e. the condensing end) causing reduced condensing area for the active fluid and reducing the overall effective length of the heat pipe. In all cases, the presence of NCG's causes the temperature difference across the heat pipe to increase dramatically, hence, increasing the overall thermal resistance of the heat pipe even if it is still able to conduct high thermal loads.

Lifetime testing aims to assess the functionality of the heat pipe over long periods, and in the case of failure, identify which of the failure modes was the main cause. This has been the predominant method by which intermediate temperature fluids have been tested. Early work at the Los Alamos Laboratory [38,40] and NASA Lewis Research Centre [42,85,88] pioneered research on experimental analysis, numerical modelling and lifetime testing for a large range of high temperature fluids in both the organic and inorganic categories. Subsequently, studies by Anderson et al. [30,82,102,104,106] are the most comprehensive work to date on reporting the testing done and the outcomes on a large range of potential medium temperature fluids. Table 2 shows a compiled chart of the key fluid/metal combinations that have been tested surrounding the medium temperature range. As far as the authors are aware, the table presents all successful tests that were reported within the medium temperature range to date. To summarise from the experimental testing detailed in Table 2, the following challenges across the medium temperature fluid range were found:

1. Mercury is toxic, has a high density, and problems have been observed with getting the mercury to wet the heat pipe wick. Limited tests have been reported in literature presumably for these reasons, though tests by Deverall et al. [83] and Yamamoto et al. [97] were reportedly successful but required a pre-heating time of up to 30 h for successful operation. Nevertheless, the dangers associated with vaporised Mercury make this option unfavourable for both laboratory experimentation and mass commercialisation. Additionally, reports detailing failures of mercury heat pipes have demonstrated the difficulties in their construction and operation [81,97,112].
2. Sulphur and Sulphur/Iodine have high viscosities, low thermal conductivities, and are chemically aggressive as demonstrated in the high level of unsuccessful tests (see Table 2). While there is some potential shown in Sulphur/Iodine test with a Stainless Steel casing, there is very limited property data availability for the mixture making it difficult to predict its potential heat pipe performance [108].
3. All the tested organic fluids start to thermally decompose between 300 °C and 400 °C in long term testing regardless of their predicted operating range [82,93,102,104,106]. Typically, they generate non-condensable gas and often the viscosity increases. At high enough temperatures, carbon deposits can be generated [106]. Jouhara et al. [87] demonstrates short term use of Dowtherm A up to 420 °C for up to 24 h and Orra et al. [113] demonstrated successful operation of Naphthalene heat pipes at 250 °C after starting up briefly at 400 °C. However, in both cases, long term life testing was not performed at temperatures above 400 °C.
4. Long term life tests show that Superalloys/TiCl4 at 300 °C, and Superalloys/AlBr3 at 400 °C are compatible. In May 2013, the AlBr3 and TiCl4 tests were running for over 6.7 years according to Anderson et al. [81]. These fluids, however, have a very low liquid transport factor (see Section 4) compared to water and their working range is limited to up to 450 °C. In comparison, it is possible to operate water heat pipes adequately at temperatures up to 300 °C at a much higher performance than TiCl4 when using an appropriate wall structure [114].
5. While other liquid metals such as Potassium and Caesium have shown some promise, with Caesium reaching operating temperatures down to 327 °C [79], a minimum diameter of 50 mm was required to overcome the low vapour density and both metals suffer from difficulties in handling and compatibility due to their extreme sensitivity to moisture which poses an explosive hazard due to hydrogen formation. Their handling often requires specialist equipment and training and can only be undertaken in inert atmospheres. The fluids themselves are already expensive to purchase and their handling requirements increases the production costs substantially and makes them unlikely to reach mass usage in the thermal management market. Despite this, there have been many recent successful developments of Caesium heat pipes [100,101,115] utilising Inconel 600 envelope material. These developments have mainly been within the nuclear market.
6. The Sodium/Potassium (Na/K) liquid metal mixture showed some initial promise but testing within the medium temperature range proved exceptionally difficult due to the 'geyser boiling' phenomenon at temperatures below 800 °C [105,109,110].

4. Categorical analysis of potential medium temperature fluids

The thermal performance of a fluid is defined by its material properties such as viscosity, surface tension, density, specific heat capacity, vapour pressure and latent heat capacity. A general assessment of the heat transport capacity of the fluid with respect to temperature can be determined through its liquid transport factor (also referred to as 'merit number', 'figure of merit' or 'heat transport capacity' in other literature [1,102]) which is a ratio of the liquid transport enhancing fluid properties (density, surface tension and latent heat of vaporisation) to the liquid transport suppressing fluid property (viscosity) [116,117]. This is given below as Eq. (1) in W/m^2.

$$M = \frac{\rho_l \sigma_l h_{fg}}{\mu_l} \tag{1}$$

The liquid transport factor provides a preliminary judgement of the effectiveness of the fluid at liquid transport (and subsequently heat transport) and an indication of the effectiveness of the fluids against others over a certain temperature range. The liquid transport factor is used in the equation relating to the maximum capillary driven heat flux ($\dot{Q}$) in a heat pipe system represented in Eq. (2) [118].

$$\dot{Q} = \left[\frac{\rho_l \sigma_l h_{fg}}{\mu_l}\right]\left[\frac{KA}{l}\right]\left[\frac{2}{r_e}\cos\theta^* - \frac{\rho_l g l}{\sigma_l}\sin\theta\right] \tag{2}$$

Within Eq. (2), it is often assumed that the contact angle between the fluid and metal casing can be approximated to ideal (i.e. $\theta^* = 0$) for the sake of simplicity. However, it is important to note that the contact angle would have an influence on the capillary pressure of the form $\frac{2\sigma_l}{r_e}\cos\theta^*$, suggesting that if a wetting angle greater than 25° is present (equating to

Table 2
Summary of key life tests completed for alternative heat pipe fluids in the medium temperature range dating back to 1960.[1]

Heat Pipe Fluid

Major component	Heat Pipe Wall Material	Dowtherm A	O-Terphenyl	N-Octane	N-methylpyrrolidone	Toluene	Biphenyl	Naphthalene	1-Fluronaphthalene	SnCl4	TiCl4	TiBr4	GaCl3	AlBr3	SbBr3	SbCl3	Water	Sulphur	S/I10%	Na/K	Mercury	Potassium	Caesium	Sodium
		OR								IN - Halides							IN - Other				IN - Liq metals			
Al	Al 3003																	[82] 600						
Al	Al 321																							
Al	Al 6061		[88] 308			[85],[88] 137	[85],[88] 241	[85],[88] 215		[85] 227	[85],[88] 165			[104] 227	[104] 227	[85],[88] 227								
Al	Al 5052													[104] 227					[107],[108] 350					
Cu	Copper	[89] 130															[89] 115							
Cu	CuNi10Fe	[80] 250				[80] 280		[96] 350									[80] 200							
Cu	Cu70Ni30																						[106] 477	
Ni	HA C22									[102] 280	[102] 300		[104] 360	[82],[103] 400										
Ni	HA C2000									[102] 280	[102] 300		[104] 360	[82],[103] 400										
Ni	HA B3									[102] 280	[102] 300		[104] 360	[82],[103] 400										
Ni	MON 400																[90] 277						[106] 477	
Ni	MON K500																[90] 277							
Ni	INC 718																							[92] 700
Ni	INC 600				[99] 320															[109] 650			[100],[101] 582	[98] 720
Mo	13CrMo44					[80] 250	[80] 250	[80],[96] 270																
Nb	Nb																							
Nb	Nb1Zr																		[107],[108] 350			[91] 600		
Fe	A-178 Steel		[85],[88] 283			[88] 119	[85],[88] 253	[85],[88] 217	[85],[88] 257	[85],[88] 227	[85],[88] 159					[85],[88] 227								
Fe	SS 304	[84] 400					[84] 400												[107],[108] 350					
Fe	SS 310S																			[110] 795				
Fe	SS 321	[80] 350		[96] 250																				
Fe	SS 316	[87] 420	[94] 380				[94] 380	[94] 380													[97] 600			
Fe	SS 316L					[80] 280	[80] 270	[80],[96] 350																
Fe	SS 347																[89] 165				[83] 330			
Fe	St35	[80] 300		[96] 230		[96] 250		[80],[96] 270																
Fe	C-Steel	[84] 325					[84] 320	[111] 320																
Ti	Ti 99.4	[80],[96] 300				[80] 250		[80],[111] 320									[80] 252							
Ti	TiAl6V4																		[107],[108] 350					
Ti	CP-Ti G1	[82] 406										[102] 380	[103] 340		[104] 227							[79] 427	[79] 327	
Ti	CP-Ti G2										[102] 227			[82],[103] 227			[90] 300		[107],[108] 250					

Key
- Compatible within the medium temperature range
- Compatible below or above medium temperature range
- Incompatible

Example
[1] <- Reference
100 <- Tested temepratrue (°C)*

OR - Organic compond
IN - Inorganic compond
HA - Hastealloy
G1 - Grade 1
G2- Grade 2
INC - Inconel
MON - Monel

*where various test temperatures occurred, the highest test point was taken (within the meadium temperature range)

Reference	Test period
[79] (Dussinger et al., 2005)	24h
[80] (Groll, 1989)	1-5 years
[81] (Anderson, 2005)	Up to 1000h
[82] (Anderson, 2007)	180 to 40000h
[83] (Deverall, 1970)	Up to 10000h
[84] (Kenney et al., 1978)	1200h to 24533h
[85] (Saaski & Owzarski, 1978)	24 to 3500h
[86] (Locci et al., 2005)	1100h to 4290h
[87] (Jouhara & Robinson, 2009)	Short term tests (likely <2h)
[88] (Saaski & Hartl, 1980)	23130h to 27750h
[89] (Basiulis et al., 1976)	1032 to 23000h
[90] (Anderson et al., 2005)	8520h
[91] (Sena & Merrigan, 1990)	1266h to 1400h
[92] (Rosenfeld et al., 2011)	10 years
[93] (Anderson et al. 2006)	Up to 11760h
[94] (Grzyll et al. 1994)	81 to 230 days
[95] (Grzyll et al. 1991)	30 to 50h
[96] (Groll et al. 1981)	Up to 1450h
[97] (Yamamoto, 1982)	Up to 30h
[98] (Jacobson 1982)	Up to 3400h
[99] (Wenyu, 2020)	Short term tests (likely <2h)
[100] (Yuxiang, 2021)	Up to 0.5h
[101] (Chen, 2022)	Short term tests (likely <2h)
[102] (Anderson 2013)	Up to 59184h
[103] (Anderson 2018)	Up to 59184h
[104] (Tarau, 2007)	Up to 3500h
[105] (Anderson, 1993)	Short term tests (likely <2h)
[106] (Anderson, 2007)	2000h to 10000h
[107] (Rosenfeld, 1992)	Short term tests (likely <2h)
[108] (Anderson, 2004)	Short term tests (likely <2h)
[109] (Guo, 2018)	Short term tests (likely <2h)
[110] (Ji, 2020)	Short term tests (likely <2h)
[111] (Vasil'ev, 1988)	Up to 3000h

[1] Fluids included in the table are those deemed most relevant to the medium temperature range by the authors (i.e. those that presented successful tests within or close to the intermediate temperature range and/or those that showed good liquid transport factors in comparison to other fluids in the same category). Unsuccessful tests of interest are also presented.

a change in capillary pressure of over 10%) this approximation may no longer be valid. For comparison purposes, it is assumed that all fluids presented below have good wetting ability with the shell and wick material. The 'wettability' of a fluid on a metal surface can be assessed through the contact angle measurement using BS EN 828 standard [119]. The wetting ability of a wick structure can also be determined by the 'capillary rise' test for a porous medium, where the wetting angle can be calculated through Eq. (3) for a known pore radius and surface tension. For further exploration of the topic of wettability, surface tension, contact angle and capillary rise can be found in standard texts [1,120].

$$\sigma_l \cos\theta \approx \frac{\rho_l g h r}{2} \tag{3}$$

The *Merit analysis* looks at the liquid transport factor of each fluid over the desired temperature range and serves as a direct comparison between their heat transport capacities. For further fluid assessment, there are two distinguishable fluid groups which all fluids can be subdivided into, these are *Organic* and *Inorganic* compounds. For the remainder of this paper, these fluid categories shall be defined as follows:

Organic compound: Any compound which contains carbon bonds.

Inorganic compound: Two or more elements combined in definite proportions with no carbon bonds.

To quantify the maximum thermal performance of each fluid, calculations were performed on the capillary, sonic, viscous, entrainment and boiling limit for a heat pipe of dimensions presented in the study by Werner et al. [114](see Table 3). The study uses heat pipes of the reported dimensions to experimentally verify the critical heat flux (also known as the boiling limit) of mesh wick heat pipes. The numerical methods detailed in the study are applied to the predictive modelling in this paper. An overview of the numerical methods used for estimating heat pipe performance as well as the fluid property data tables used for all the fluid analysed in this paper can be found in the supplementary material where the fluid property data is taken from Yaws et al. [121]. Within each category, the fluids presented are those which have had proven successful compatibility within the medium temperature range.

Table 3
Heat pipe dimensions as specified in study by Werner et al. [114].

Measurement	Value
Heat Pipe Length (m):	0.46
Evaporator Length (m):	0.1
Condenser Length (m):	0.15
Adiabatic Length (m):	0.21
Effective Length (m):	0.335
Diameter (mm):	12
Wall Thickness (mm):	0.8
Wall Conductivity (W/m K):	29
Orientation:	Horizontal
Screen Conductivity (W/m K):	50
Screen count (wires per 25.5 mm (1 in.):	200
Number of wraps:	3

4.1. Organic fluids & organic mixtures

Interest in organic fluids for use in heat pipes has a long history dating back to work by Saaski et al. at the NASA Lewis Research centre [37,85,88], Grzyll et al. at the Mainstream Engineering Corporation [94,116] and Kenney et al. at the University of New Mexico [84]. Much of this work investigates the use of organic fluids up to 400 °C using the theory of thermal stability developed by Johns et al. [122], which is further discussed in Section 5.

The most recent research directed towards identifying and testing organic fluids for the intermediate temperature range have origin in various institutions in the USA. Various works by Anderson et al.

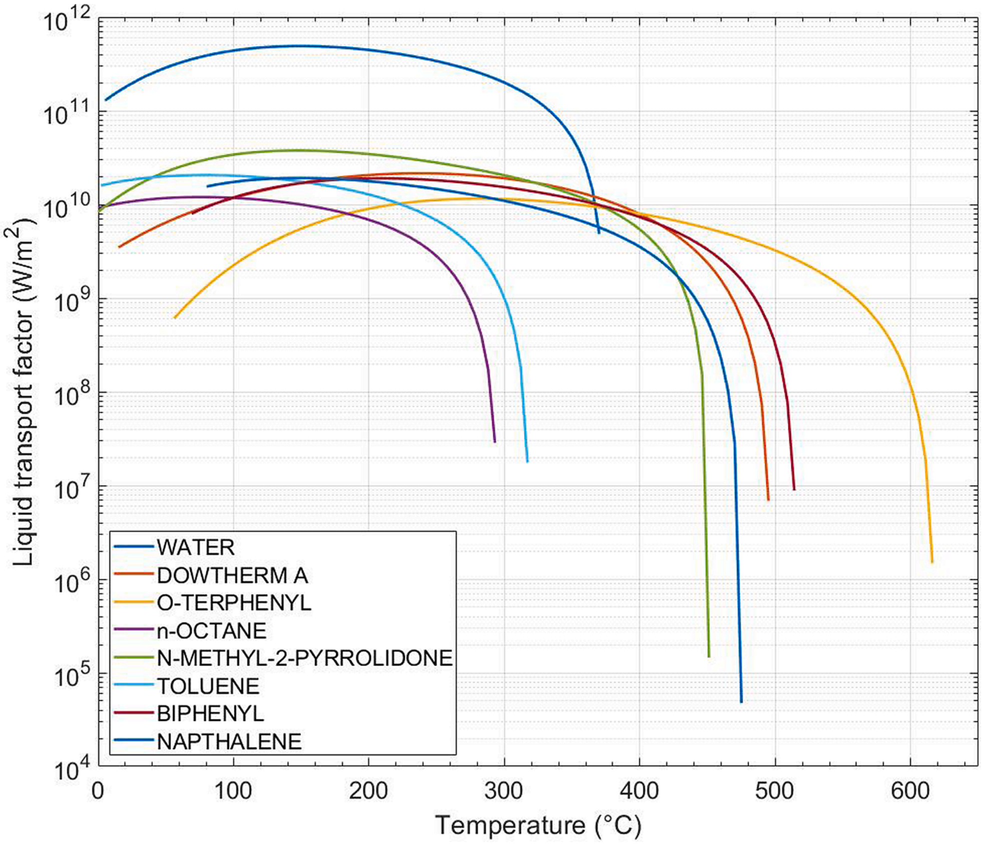

Fig. 6. Liquid transport factor for main organic fluids explored for use in the medium temperature range.

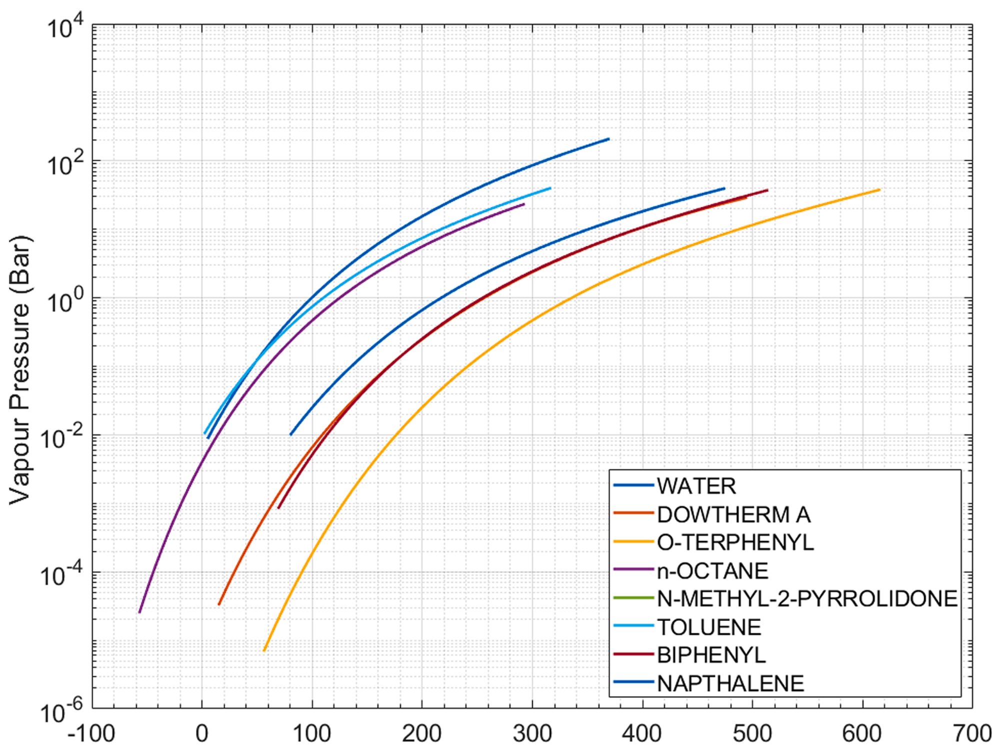

Fig. 7. Vapour pressure for main organic fluids explored for use in the medium temperature range.

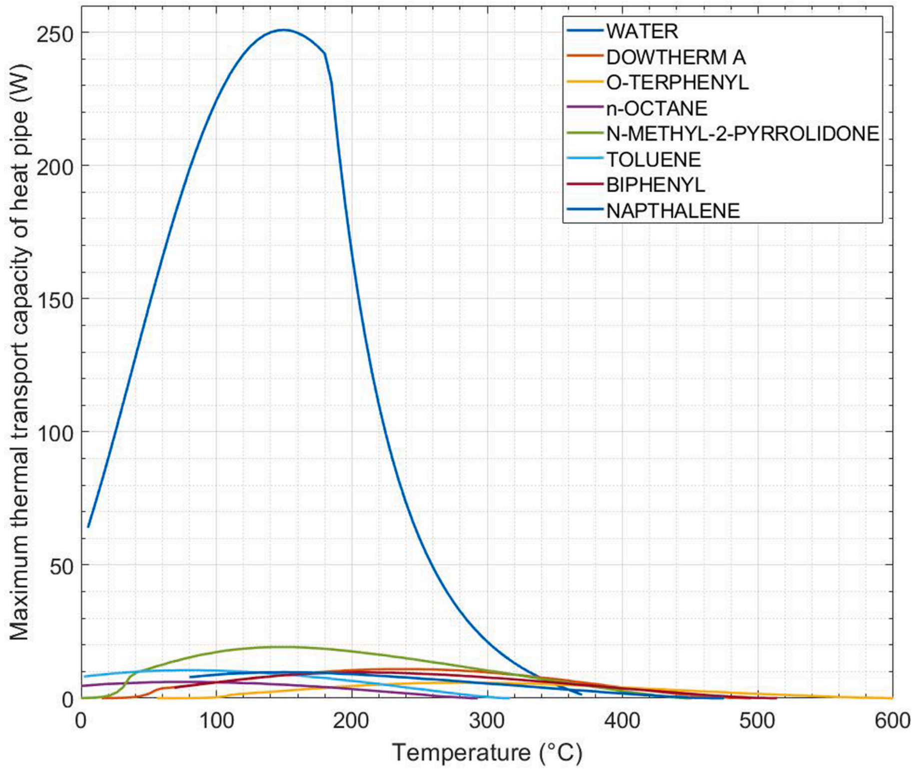

Fig. 8. Maximum thermal transport capacity for main organic fluids explored for use in the medium temperature range. Modelled with heat pipe dimensions presented in the study by Werner et al. [114] (see Table 3).

[82,93,102,104,106] Devarakonda et al. [123], Rosenfeld et al. [107], Groll et al. [80] and Vasil'ev et al. [111] set the groundwork for investigation into novel heat pipe fluids including (but not limited to) organic fluids. Table 4 shows a summary of all successful compatibility results for organic fluids falling within the medium temperature range. The highest successfully tested temperature for organic fluids is 400 °C.

The liquid transport factor for each fluid highlighted in Table 4 is shown in Fig. 6, with water as a reference point. Here it can be seen that organic fluids all tend to have a substantially lower liquid transport factor as compared to water. The eutectic mixture Dowtherm-A showed the highest factor out of the organic fluids presented, though the critical temperature is reached at around 500 °C. O-terphenyl, on the other hand, has a critical temperature beyond 600 °C, but its liquid transport factor is one of the lowest. However, it is also important to note that the thermal degradation of the fluid must also be taken into account. It can be observed throughout all the cited studies that organic compounds tend to suffer from thermal decomposition at temperatures above 400 °C.

The vapour pressure of the same fluids is shown in Fig. 7. Here it can be seen that all fluids present favourable conditions over their working range, showing maximum pressures of up to 40 bar. They all also show adequate pressures at the lowest medium temperature point (300 °C). By comparison, water can reach pressures of up to 200 bar at the high end of its working temperature range.

Lastly, Fig. 8 shows the maximum thermal power limit for each fluid when modelled in a 12 mm dimeter mesh heat pipe of dimensions equals those presented by Werner et al. [114]. Here it can be seen that the heat pipe performance of the organic compounds is low in all cases, particularly when compared to that of water. There appears to be no substantial benefit to using these organic compounds at temperatures below 300 °C as water would outperform all presented organic fluids. Although their range does extend into the medium temperature range, the transport capacity of all fluids does not exceed 20 W (which in this case equates to a heat flux of 0.53 W/cm^2 at the evaporator). While their performance could be improved with the use of sintered wicks, it is still a somewhat underwhelming evaluation for these fluids, in addition to the fact that none of the fluids demonstrate the capability for operation over the entire range.

In addition to the tests presented in Table 4, there have been some more recent tests on these and other organic fluids at temperatures reaching up to 450 °C (Dowtherm A [106,124], P-Terphenyl [84], Diphenyl [102]) as seen in Table 2. However, current studies are yet to present a successful long term result above 400 °C. In each case, it has been shown that the heat pipe failure mode stems from the thermal decomposition of the fluid itself rather than reaction with the wall material. From this, it can be surmised that the currently identified viable organic medium temperature fluids have been empirically proven to only have a functioning capacity of no more than 400 °C for long term use. While this does give some overlap into the medium temperature range, it is unlikely that an organic fluid would be able to reliably cover the entire temperature range. Moreover, their significantly lower liquid transport factor compared to water limits their usefulness at temperatures lower than 320 °C giving the best performing organic fluids only an 80 °C useful working range (form 320 °C to 400 °C).

4.2. Inorganic fluids

Inorganic fluids have been analysed and tested largely alongside organics in studies by Saaski et al. [37,85,88], Grzyll et al. [94,116], Kenney et al. [84] and Reid et al. at the Los Alamos Nuclear Laboratory [40]. Within the 'inorganic' category there are two main sub-categories which will be explored. These categories are halogenated alkanes (also referred to as 'halides') and liquid metals. Additionally, a series of inorganic mixtures are also explored.

Table 4
Summary of experimentally verified organic fluids tested in the medium temperature range.

Fluid	Theoretical working range (°C)	Melting point (°C)	Boiling point (°C)	Critical temp (°C)	Author(s)	Summary
Dowtherm A (Diphyl/ Therminol VP-1)	150–450	12	257	497	*Anderson et al.* [82,106]	- Good compatibility with **SS304L** at **345 °C** for up to **10000 h** - Gas generation above **400 °C** due to thermal decomposition
					Groll et al. [96]	- Moderate compatibility with **St35** at temperatures up to **270 °C** for up to **1350 h** - Good compatibility with **Ti994** and **CuNi10Fe** at temperatures up to **300 °C** for up to **30 h**
					Kenney et al. [84]	- Good compatibility with **SS304** at **400 °C** for up to **1200 h** - Good compatibility with **SS304** at **268 °C** for up to **24533 h** - Good compatibility with **Carbon Steel** at **250 °C** for up to **8382 h**
					Groll et al. [80]	- Moderate compatibility with **St35** at **270 °C** and **X10CrNiTi189** at **300 °C** for up to **5 years** - Good compatibility with **Ti99.4** at **270 °C** for up to **1 year**
Naphthalene	135–350	80	218	475.2	*Vasil'ev et al.* [111]	- Good compatibility with **Titanium** and **Steel C-20** at **320 °C** for up to **3000 h**
					Gryzll et al. [94]	- Good compatibility with **St35** at **400 °C** for up to **1200 h**
					Groll et al. [80]	- Good compatibility with **Ti99.4** and **X2CrNiMo1812** at **320 °C** for up to **1 year** and with **St35** at **270 °C** for up to **3 years**
					Saaski et al. [88]	- Good compatibility with **Al6061** and **Carbon Steel** at **215 °C** for up to **27750 h**
Biphenyl (or Diphenyl)	250–400	69.2	255	~506	*Gryzll et al.* [94]	- Good compatibility with **SS316** at **350 °C (mean)** for up to **230 days**
					Groll et al. [80]	- Good compatibility with **13CrMo44** at **250 °C** and **X2CrNiMo1812** at **270 °C** for up to **1 year**
					Saaski et al. [88]	- Moderate compatibility with **Al6061** at **245 °C** for **10000 h**
					Kenney et al. [84]	- Good compatibility with **SS304** at **400 °C** for up to **1200 h** - Good compatibility with **Carbon Steel** at **320 °C** for up to **4648 h**
O-Terphenyl	250–400	~55	732.2	~583	*Gryzll et al.* [94]	- Good compatibility with **SS316** at **350 °C** for **230 days**
N-Octane	0–300	−57	125.6	295	*Groll et al.* [96]	- Good compatibility with **St35** and **SS 321** at up to **250 °C** for **1350 days**
N-Methyl-2-Pyrrolidone	0–450	−24	202	451	*Wenyu et al.* [99]	- Good compatibility with **Inconel 600** at **320 °C** for short durations
Toluene	0–300	−95	110.6	592	*Groll et al.* [80]	- Good compatibility with **Ti99.4, SS 316L, CuNi10Fe, 13CrMo44** at up to **280 °C** for up to **3 years**
					Groll et al. [96]	- Good compatibility with **St35** at **250 °C** for up to **730 days**
					Saaski et al. [85,88]	- Incompatible with **A-178 Steel** at **119 °C** - Good compatibility with **Al 6061** at **137 °C** for **2.5 years**
1-Fluronapthalene	0–400	−13	215	–	*Saaski et al.* [85,88]	- Good compatibility with **A-178 Steel** at **257 °C** for **2.5 years**

4.3. *Halides*

The most recent tests conducted on halide fluids are those undertaken by Anderson et al. [82,102,108]. In this work, a large range of fluids were selected for lifetime testing, mostly resulting in incompatible matches at high temperatures. The most promising results from Anderson as well as previous studies which have tested at or near the medium temperature range are presented in Table 5. In these studies, it was found that many halides show good compatibility with the Nickel alloy 'Hastelloy' within the medium temperature range.

The liquid transport factor for each of the halide fluids shortlisted in this study can be found in Fig. 9, with water included as a baseline. In all cases, the indicated halide liquid transport factor is shown to be substantially lower than that of water. Observing Fig. 10, the vapour pressure are within reasonable range, mostly remaining below the maximum vapour pressure of water with the exception of high temperatures of Antimony Tribromide, where its higher vapour pressure relative to the other halides must be noted. Overall, Antimony Tribromide shows the largest potential operating range as well as one of the highest overall liquid transport factors (see Figs. 9 and 11). This indicates that, out of the empirically tested halide fluids thus far, Antimony Tribromide appears to be the strongest contender for use as a heat pipe fluid.

When comparing their capillary limit performance for a 12 mm diameter mesh heat pipe in Fig. 11, it can be seen that a maximum heat transfer of 22 W (0.58 W/cm^2) can be achieved using Antimony Tribromide. These results indicate that the use of these halides are limited to very low heat flux density applications above 320 °C. As far as the authors are aware, there have been no further testing with halides to date which have been published in the open literature. In Werner's doctoral thesis, however, several other potential halides were identified from theoretical analysis which may have increased heat transport performance in the medium temeprature range, these are; Bismuth Trichloride, Ruthenium Pentafluoride, Rhenium Heptoxide and Rhenium Heptafluoride [47]. Unfortunately, non of these have yet undergone experimental analysis and they all tend to be substantially more expensive than the currently tested halides.

4.4. *Liquid metals*

In general, liquid metals have a start-up temperature much higher than 600 °C, however there are some key exceptions. Table 6 shows some common liquid metal elements and their working range.

Observing Table 6, there are distinctly four metals which can theoretically operate within the medium temperature range, i.e. Mercury, Caesium, Rubidium and Potassium. As seen in Fig. 12, their liquid

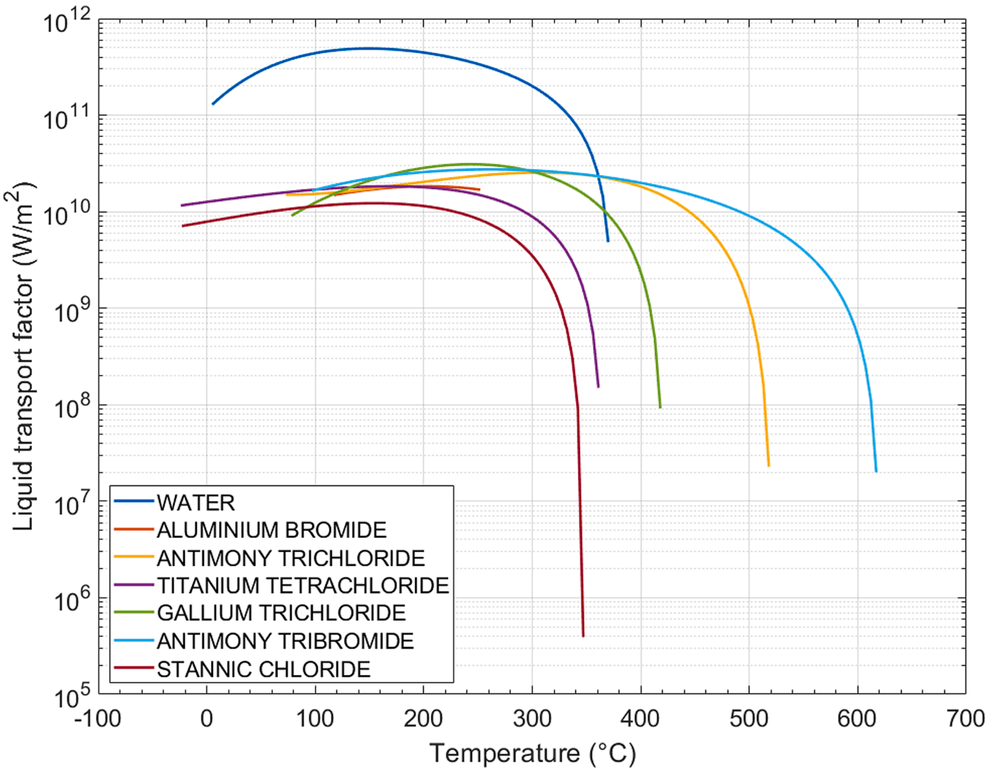

Fig. 9. Liquid transport factor for main halide fluids explored for use in the medium temperature range.

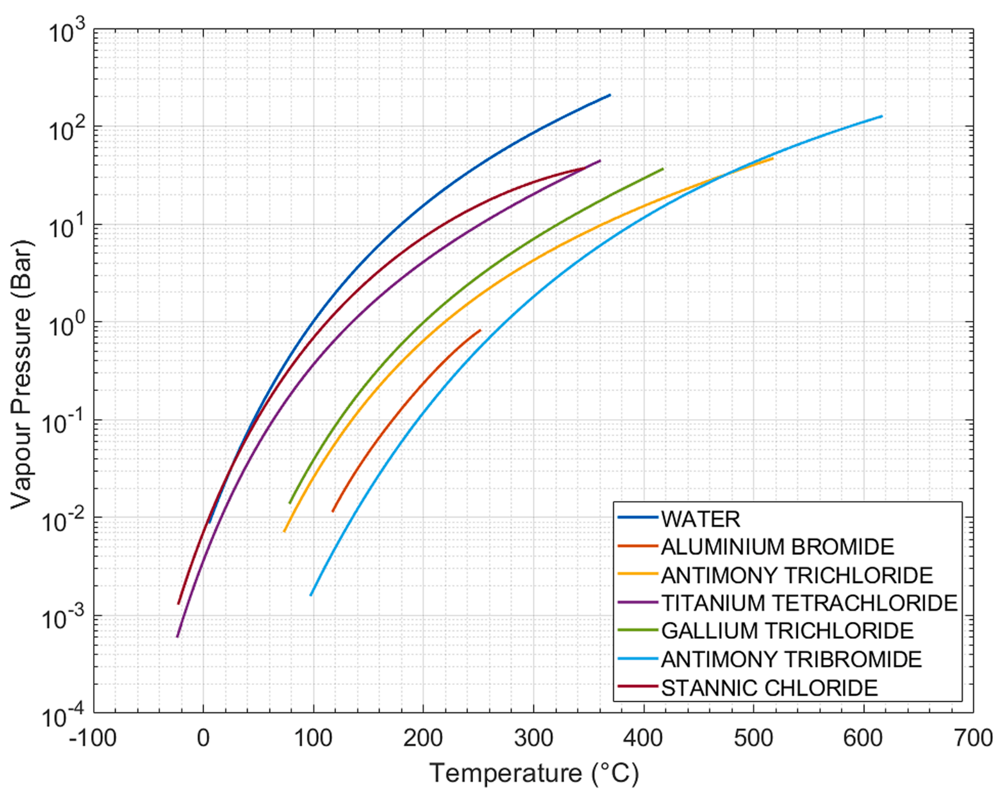

Fig. 10. Vapour pressure for main halides explored for use in the medium temperature range.

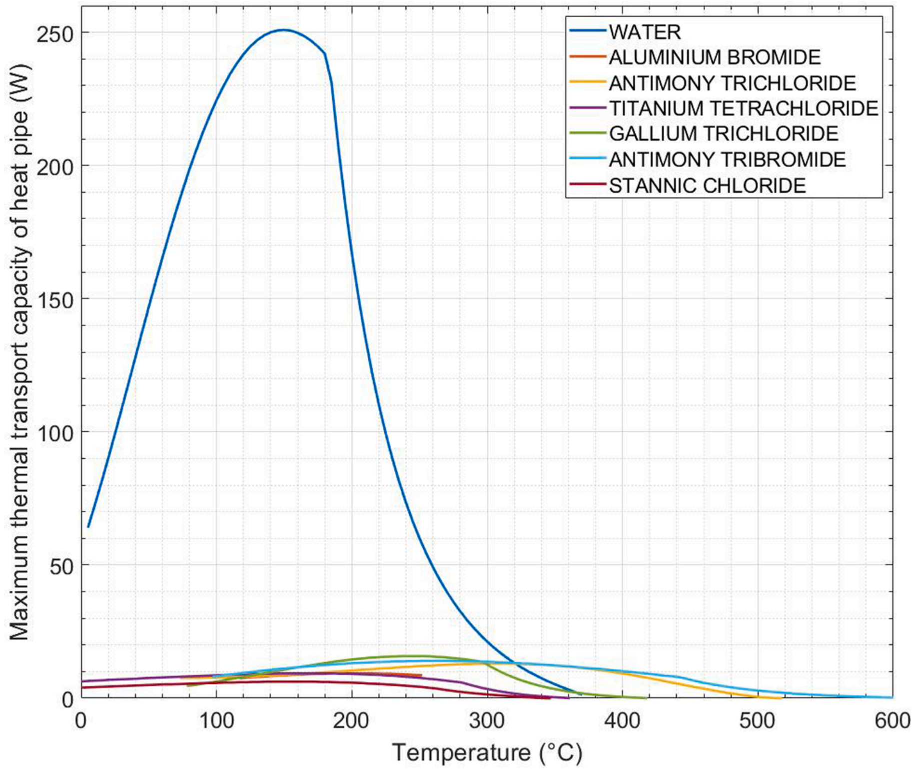

Fig. 11. Maximum thermal transport capacity for main halides explored for use in the medium temperature range. Modelled with heat pipe dimensions presented in the study by Werner et al. [114] (see Table 3).

Table 5
Summary of experimentally verified halides in the medium temperature range.

Fluid	Theoretical working range (°C)	Melting point (°C)	Boiling point (°C)	Critical temperature (°C)	Author(s)	Summary
Aluminium Tribromide (AlBr3)	120–420	117	256	490	*Anderson et al.* [102]	- Good compatibility with **HastC22** and **C2000** at **400 °C** for up to **58992 h** - Incompatible with **HastB3** at **400 °C**
					Locci et al. [86]	- Incompatible with **Al 6061 and CPTi2.** Ongoing tests with, **Al-5052** (at the time).
Antimony Trichloride (SbCl3)	100–500	75	220	521	*Saaski et al.* [85,88]	- Incompatible with **Al 6061** and **A-178 Steel** at **277 °C**
Titanium Tetrachloride (TiCl4)	100–300	−24	136	365	*Anderson et al.* [106]	- Good compatibility with **HastC22, HastC2000** at **300 °C** for up to **2000 h**
					Saaski et al. [88]	- Good compatibility with **A-178 Steel** at **159 °C** for up to **28540 h** - Incompatible with **Al 6061** at **165 °C**
Gallium Trichloride (GaCl3)	90–400	77.8	201	421	*Tarau et al.* [104]	- Incompatible with **HastC22, C2000** and **B3** at **360 °C**
					Anderson et al. [103]	- Incompatible with **CpTi** at **340 °C**
Titanium Tetrabromide (TiBr4)	50–350	39	230	523	*Anderson et al.* [102]	- Incompatible with **Cp-Ti** at **380 °C**
Stannic Chloride (SnCl4)	50–350	–33	115	319	*Anderson et al.* [102]	- Good compatibility with **Mild Steel** and **304 SS** at **156 °C** - Incompatible with **C22, C2000** and **B3** at **280 °C** - Incompatible with **Al 6061** at **227 °C**
Antimony Tribromide (SbBr3)	60–600	97	280	905	*Tarau et al.* [104]	- Incompatible with **Ti** at **227 °C**
					Anderson et al. [82]	- Incompatible with **Al 6061** at **227 °C**

Table 6
Common heat pipe liquid metals. Data from Faghri et al. [14].

Fluid	Melting point (°C)	Boiling point (at 1 atm) (°C)	Working range (°C)
Mercury	−39	361	250–650
Caesium	29	670	350–900
Rubidium	40	686	400–1600
Potassium	62	774	500–1000
Sodium	98	892	600–1200
Lithium	179	1340	1000–1800
Calcium	839	1489	1127–1827
Lead	328	1740	1397–1927
Indium	157	2080	1727–2727
Silver	960	2212	1800–2300

transport factor also shows a promising outlook as compared to water. It can be seen that they are potentially able to span a large temperature range, including the 'medium' range in question. The most obvious contenders from initial observation of Table 6 would be Mercury and Caesium as these metals span the entire working range, however, Figs. 12 and 14 shows that Mercury and Potassium have the highest heat transport abillity. Generally, the liquid metal vapour pressures remain relatively low in the medium temperature region for all fluids except Mercury (see Fig. 13). Although this would potentially allow for ultra thin wall structures to be used, it also is the driving reason behind the need for large heat pipe diameters to overcome the sonic limitation. Naturally, liquid metals have indeed been the subject of many trials as heat pipe fluids, but unfortunately, each of these come with their own set of drawbacks which is detailed in Table 7.

Within the medium temperature range, a report by Sena et al. [91] shows successful operation of a Potassium heat pipe with Niobium and Tantalum wall materials at temperatures down to 522 °C. The most promising studies in the medium temperature range are those presented by Dussinger et al. [79], where Potassium and Caesium heat pipes were constructed for short term testing. The results showed preliminary successful compatibility results of the Caesium heat pipe down to 350 °C and of the Potassium heat pipe down to 430 °C (see Table 7).

4.5. Inorganic mixtures & others

Lastly, several studies have given reference to the potential use of azeotropic and eutectic mixtures to tailor the fluid properties for use in the medium temperature range [82,102,105]. Sulphur, which can be described as a 'multivalent non-metal' within the inorganic category, has been widely explored and is one of the main elements used in the development of azeotropic mixtures in the medium temperature range. While Sulphur presents favourable thermal properties, it has a unique mechanism by which it tends to polymerise in liquid state at temperatures above 475 °C. This polymerisation causes an increase in liquid viscosity of high magnitude which impedes effective heat pipe operation. Researchers found that the addition of Iodine can help to reduce polymerisation of the fluid and allow for more favourable operation as a heat pipe fluid. Another mixture of note is Sodium/Potassium (NaK) which has had an increasing interest over the years [105,109,110]. In all cases for the NaK mixture though, major instabilities in the evaporator region were reported within the medium temperature range due to geyser boiling, leading to temperature difference of up to 134 °C across the evaporator section alone. Another issue with all inorganic mixtures is that they currently suffer from a lack of property data, hence, it is currently not possible to derive liquid transport factors, vapour pressure curves and predicted performances for these fluids. Further studies should be directed into analysing the properties of these fluids. Table 8 summarises the principal studies conducted on these fluid mixtures to date.

5. Example of a heat pipe fluid analysis process

While numerical modelling is of course a crucial exercise in academic studies for novel heat pipe fluids, conducting an extensive fluid analysis prior to this can bring a substantial benefit to heat pipe design in both an academic and commercial setting. The use of this process can help to ensure that the heat pipe will not only meet the temperatures and power carrying requirements, but also be compliant to safety standards, be able to withstand the estimated operation life span and provide cost effectiveness. For this reason, it may be useful to implement a standardised analysis process by which fluids can be assessed given the constraints of a particular application as well as centrally catalogued location for

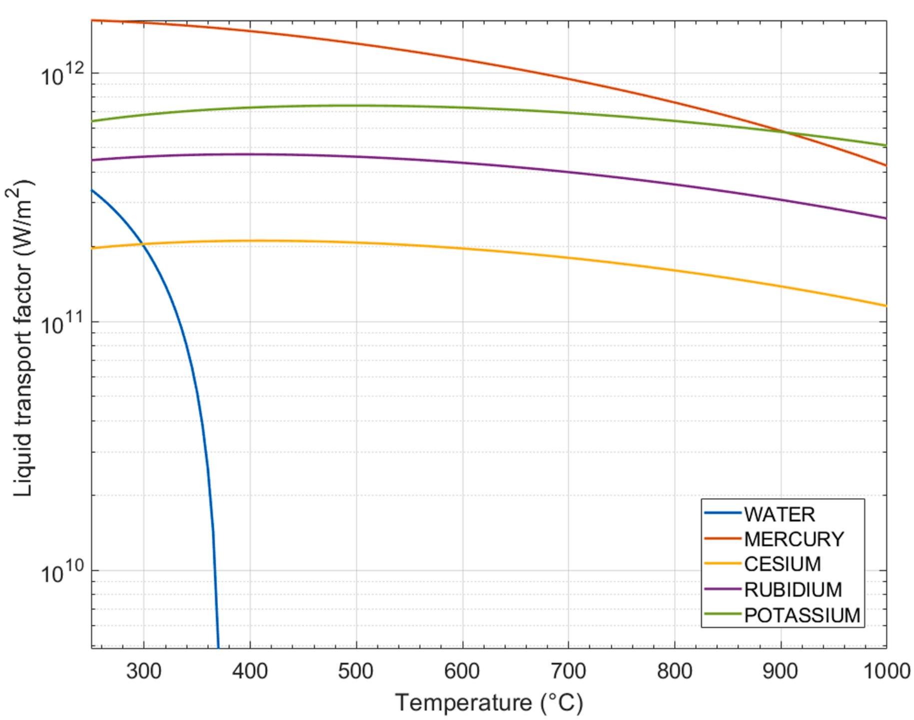

Fig. 12. Liquid transport factor for main liquid metal fluids explored for use in the medium temperature range.

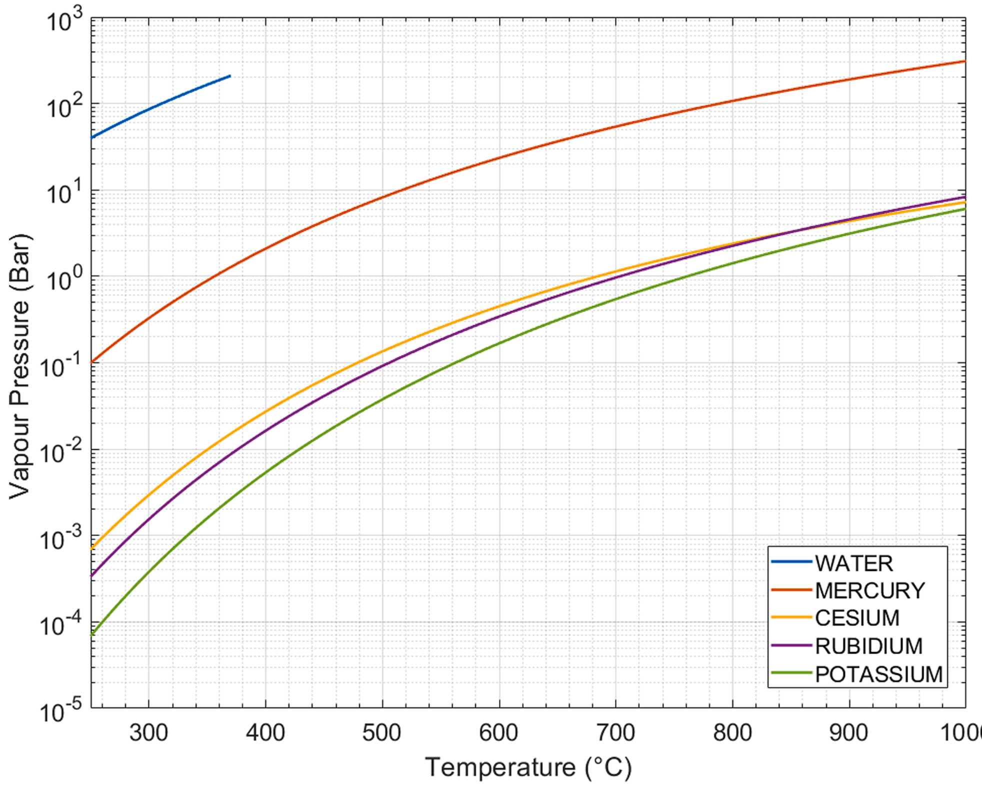

Fig. 13. Vapour pressure for main liquid metals explored for use in the medium temperature range.

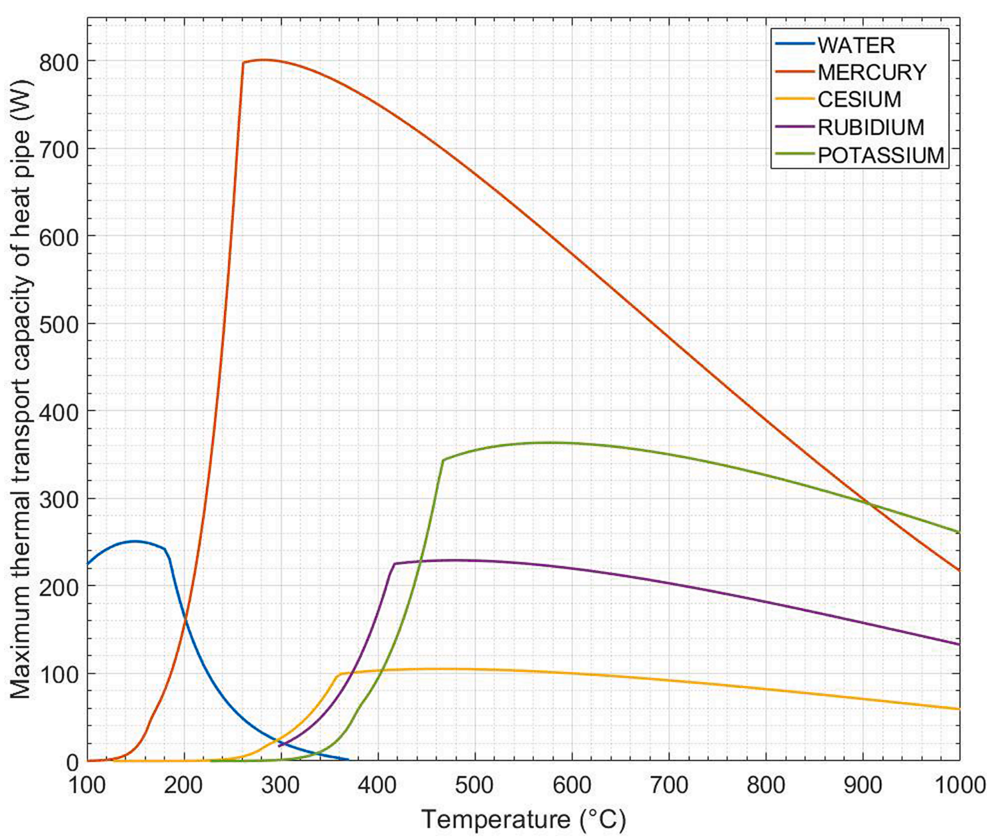

Fig. 14. Maximum thermal transport capacity for main liquid metals explored for use in the medium temperature range. Modelled with heat pipe dimensions presented in the study by Werner et al. [114] (see Table 3).

Table 7
Summary of experimentally verified liquid metals tested in the medium temperature range.

Fluid	Theoretical working Temperature range (°C)	Melting point (°C)	Boiling point (°C)	Critical temperature (°C)	Author(s)	Summary
Mercury	0–1300	−38.9	356.6	1461.9	*Yamamoto et al.* [97]	- Lowest tested temperature: **350 °C** - No compatible metals proven for long term use, high corrosion.
					Deverall et al. [83]	- Good compatibility with **SS304** and **SS347** at **330 °C** for **1000 h** - Only partial wetting of wick up to 400 °C, full wetting at 500 °C
Caesium	150–1500	28.5	690	1775	*Dussinger et al.* [79]	- A Caesium heat pipe was tested at **350 °C** for **48 h** with no sign of degradation, though no long-term results are yet presented.
					Chen et al. [101,115]	- Successful compatibility testing down to **582 °C** with **Inconel 600**
Rubidium	40–1500	39.31	704.9	1838	*El-Genk et al.* [125]	- A theoretical analysis of rubidium heat pipes is conducted but no experimental validation as of yet. No proof of compatible long-term metals for use with Rubidium.
Potassium	230–1700	65.2	763.9	1949.9	*Dussinger et al.* [79]	- A Potassium heat pipe was tested at **430 °C** for **48 h** with no sign of degradation, though no long-term results were presented.

Table 8
Summary of experimentally verified mixtures tested in the medium temperature range.

Fluid	Theoretical working Temperature range (°C)	Melting point (°C)	Boiling point (°C)	Critical temperature (°C)	Author(s)	Summary
S/I10 (Sulphur/ Iodine)	350–700	116.8	–	–	*Anderson et al.* [102,108]	- Lowest successful tested temperature: **350 °C**- Tested compatible metals: Al 6061, A-178 Steel, 316 SS
Sulphur	200–800	115.2	444.7	1039.9	*Anderson et al.* [102,108]	- Highly toxic, Low vapour pressures, High liquid viscosity - The major factor contribution to its inadequate use in heat pipes is the incredibly high liquid viscosity over almost all the working temperature range.
Na/K (Sodium/ Potassium)	400–900	5	814	–	*Anderson et al.* [105]	- Peripheral evaporation (or geyser boiling) of Potassium can cause a high temperature fluctuation of up to 95 K across the evaporator.
					Guo et al. [109]	- The heat pipe was affected by geyser boiling at temperature below 875 °C causing temperature differences of up to 134 °C across the evaporator.
					Ji et al. [110]	- Successful implementation of Na/K in pulsating heat pipes at temperatures down to 500 °C.

previous testing done. This is additionally useful when it comes to assessing new fluids which have not yet been considered or comparing a large number of fluids against each other. This section presents the tools commonly used to assess the adequacy of a fluid and proposes a framework by which fluids can undergo a standard assessment for any application.

5.1. Fluid/metal compatibility and fluid stability prediction

5.1.1. Organic compounds

The modelling and prediction of the decomposition of organic compounds is a complex process. The dominant mode of failure is thermal degradation as observed in most lifetime tests presented in Table 2. The principle behind predicting the point of degradation is to determine the rate of pyrolysis of a compound at a given temperature, based on the activation energy of the various bonds within the molecule to break the molecule into its constituents. In the Rice, Ramsper and Kassel (RRK) model [126], the first order rate of bond breakage is given by Eq. (4).

$$R_1 = Ae^{\frac{E^+}{RT}} \tag{4}$$

Sources of complexity and error in the modelling of these reactions come from intermediate stage reactions, reaction with impurities or decomposed products and the heterogeneous nature of the container should residual air still be present [84]. More robust models exist to determine more precisely the effect of intermediate reactions. However, this simplified method is still useful to determine a rough breakdown temperature for a given fluid under ideal conditions.

5.1.2. Inorganic compounds

The thermal stability of inorganic compounds tends to be very good, with the distinct advantage of no non-condensable gas (NCG) formation on decomposition. Hence, the main factor to determine the suitability of the inorganic fluids as working fluids is their reactions with the metal envelope. The reactivity of a metal halide in contact with a metal container is characterised by their relative stabilities. A general reaction between a liquid halide and a metal wall can be expressed by Eq. (5) below, [37].

$$fM_a + gM_bX_c \leftrightarrow fM_aX_{cp} + gM_b \tag{5}$$

Where M_bX_c is the metal halide and M_a is the wall metal. The free energy change during the reaction can be estimated by comparing the EMF potential of the reactant and product halide compound as seen below.

$$\Delta E = \Delta E^0 - \frac{RT}{nF}\ln\left[\left(\frac{(M_aX_{cp})^f(M_b)^g}{(M_a)^f(M_bX_c)^g}\right)\right] \tag{6}$$

The overall EMF of a reaction can be found through Eq. (6), though it is often the case that the second term in this equation can be neglected when dealing with insoluble compounds (i.e. one element in the reaction is in solid state) as the relative concentrations of each compound will remain at unity. This reduces the overall reaction EMF to Eq. (7).

$$\Delta E^0 = E_p(producthalide) - E_p(initialhalide) \tag{7}$$

E_p is obtained experimentally through electrolysis reactions and can often be found in property data tables. If the result returns a positive value, then spontaneous reaction will occur between the wall and the fluid. If the EMF is strongly negative the reaction between the fluid and the wall is insignificant. From this it can be inferred that the ideal combination would be to have fluids with high decomposition potentials and walls which form halide products of low decomposition potentials.

Another mechanism by which fluid/case reaction can occur is

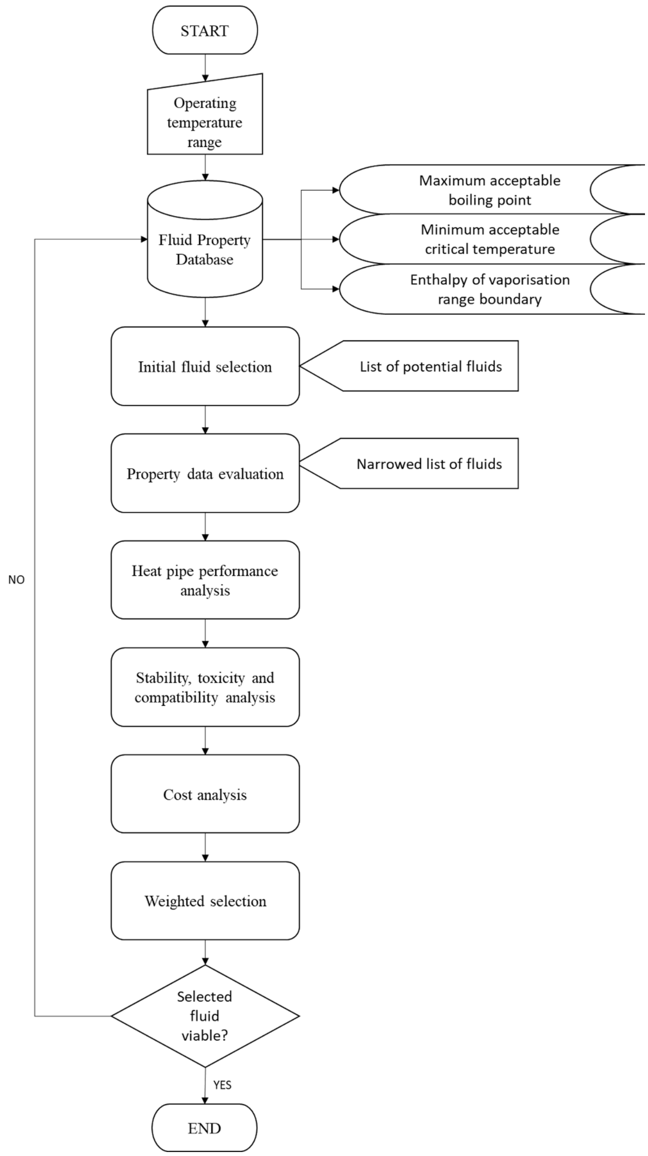

Fig. 15. Fluid analysis and selection process.

through the dissolution of the wall and wick material into the heated liquid solution as demonstrated by Meng et al. [127] with liquid lithium at temperatures above 320 °C. To estimate the solubility of a solid into liquid, Eq. (8) is used, derived from simple mass flux transfer experiments.

$$J = h_m(A_0 - A) \tag{8}$$

Values of J lower than $1\mu m/h$ indicate exceptional corrosion resistance. Meng et al. [127] demonstrated that Tungsten, Molybdenum and Stainless Steel 304 all fall below $1\mu m/h$ mass flux when exposed to liquified lithium at 600 K for up to 1320 h.

5.2. Toxicity and cost analysis

Generally, toxicity data for a specific chemical is provided through their Material Safety Datasheet (MSD). These should serve as an indication for the level of precaution necessary when handling any chemical. When a chemical is considered high risk, additional safety guidelines, protocols and necessary certifications can be found through an appropriate national health and safety executive agency.

The cost analysis aims to either highlight any cost prohibitive chemicals or serve as an additional metric when comparing chemicals of similar performance. Some examples of assessed costs can include items such as:

- Cost of the chemical per kg
- Additional costs associated with handling high risk chemicals (specialist equipment necessary, necessary personnel training, storage costs, disposal costs)
- Relative cost of compatible metal wall structures including cost per kg, minimum wall thickness required and specialist machining and/or joining requirements

5.3. Fluid assessment process

The required property data for this process is the liquid and vapour density, liquid and vapour viscosity, liquid and vapour thermal conductivity, enthalpy of vaporisation, saturation pressure and surface tension for each fluid. The polynomial constants for the property data used in this study can be found in the supplementary material. Once a narrowed selection of fluids is made from this analysis there are several further criteria to be assessed to make a weighted comparison. These comprise of both a thermal performance and environment assessment. The various criteria for each of these categories are detailed as follows:

Thermal performance assessment criteria:

- Melting point/boiling point/critical temperature
- Liquid transport factor
- Vapour pressure

Environmental assessment criteria:

- Fluid stability/thermal decomposition
- Fluid Compatibility with wall material
- Toxicity and handling difficulty
- Economic assessment

Any application must address these criteria in the heat pipe fluid selection. Fig. 15 shows a typical fluid analysis process for identifying, comparing and selecting key fluids from an available fluid database using the numerical methods previously presented in this paper. In addition to comparing the absolute values of each criterion, a weighted selection can also help to derive a solution geared towards the specific techno-economic priorities of the participating organisations. It is clear from the flow chart presented in Fig. 15 that a robust and extensive fluid property database, which is continually updated with novel fluids as they emerge, is key to identifying the best suitable fluid for a particular temperature range as this forms the basis to which all other analytical processes are derived. Some advantages of using a system such as this in the development and modelling of novel heat pipes are:

- It provides rapid analysis and robust selection of fluid/metal combination for any given application based on large fluid/metal databases.
- It provides a method by which newly developed fluids can be directly compared to existing ones in a standardised manner.
- It allows alternative fluids to be explored for existing applications which could improve the performance, cost-effectiveness or longevity of the heat pipe.
- The weighted selection can be adapted to cater for changing priorities (e.g. weight, cost, performance, geometry, etc.).

It is important to also note that some limitations of this method are:

- The number of fluids is limited by the ones available within the database, hence the database must be managed and updated to include the property data of new fluids as they become available.

- Since the heat pipe performance calculations are standardised, there are several simplifications assumptions which must be considered. These may not be valid for certain fluids and care must be taken when analysing heat pipe performance.
- The numerical methods used in the process (see supplementary material) are for standard heat pipes only, these must be adapted when analysing bent, flattened, hybrid wick, loop, variable conductance, rotating or any other form of heat pipe.

8. Current status, challenges and the future direction of technology

Numerous previous studies have shown that *Organic* fluids are least likely to cover the temperature gap successfully due to their susceptibility to thermal degradation at temperatures above 400 °C. Within the *Inorganic* category, seven key halides were analysed which have undergone compatibility testing in past literature. When conducting a numerical analysis of these fluids it was found that their performance is somewhat underwhelming both in heat carrying capacity and temperature span. Out of the halides analysed, Antimony Tribromide showed the best potential performance, though the maximum potential heat flux density that can be handled using a 12 mm diameter mesh wick heat pipe did not exceed 0.58 W/cm^2 with a maximum useful temperature of up to around 480 °C. Also, within the inorganic category, liquid metals such as Mercury, Rubidium, Caesium and Potassium showed a much more promising outlook initially from numerical analysis, though many studies have shown that they are still burdened by practical issues such as difficulty in handling, reaction with common wall materials and low performance in the 300–450 °C due to their sonic limit. Some potential fluid mixtures such as Sulphur/Iodine and Sodium/Potassium show great promise within the limited testing done, however have been very rarely studied in literature making it difficult to extract their fluid property change with temperature and therefore predict their performance.

In the authors' opinion, while the efforts so far have been meaningful, they have also been largely isolated. The promotion of long-standing collaborations between industry and academia is key. Also, the development of central databases and heat pipe modelling tools such as those developed by Werner [47] would not only accelerate the analysis and experimentation of novel fluids but also aid in promoting the use of heat pipes in a wider range of applications and attracting more external investments. These tools include heat pipe modelling capability and comparative performance analysis using a database of over 500 fluids. The tools were developed for the purpose of performing parametric analysis for the development and optimisation of heat pipes in any temperature range as well as providing the ability to compare the performance of newly developed medium temperature fluids against the currently existing ones presented in this study. The availability of these tools will become public in 2024.

9. Conclusions

This work has overviewed the increasing requirements for heat pipes of intermediate temperature range and outlined the research that has been conducted thus far in this area. A framework for fluid analysis for heat pipes in any temperature range has also been suggested which aims to aid in both academic and commercial heat pipes research activities. Some of the critical challenges which we are currently facing in the development of a viable widely commercial medium temperature heat pipes are highlighted. A cross analysis of the major studies that have tested alternative heat pipe fluids in this temperature range has been undertaken and catalogue of the most promising fluids is presented in order to benchmark the work for future development. The cross examination of over 120 of the most relevant studies on medium temperature heat pipe development has reached the following conclusions:

- Out of the currently experimentally verified fluids, liquid metals such as Mercury, Caesium and Potassium clearly have the best heat transporting ability. Standardised modelling of all presented fluids show that liquid metals are able to carry from 5 to 50× the power of the nearest best performing fluid in the organic or halide category and are theoretically able to cover the entire medium temperature range. A limited number of experimental tests verify their use down to 330 °C (Mercury) and 327 °C (Caesium) and their long-term compatibility with common metals such as Stainless Steel and Monel. Their use is still limited by the relatively large minimum heat pipe diameter needed and testing is limited by the many health dangers associated with these fluids. Despite this, these remain the currently most viable options.
- A long history of experimentation with organic fluids suggests that they are the most unlikely fluid category to cover the entirety of the medium temperature range. Their performance in the comparative modelling showed very low power transport capability and few are able to cover the entire medium temperature range adequately.
- Halide fluids have been central to many long-term compatibility test efforts, however up to now there are very few that show signs of good compatibility with common metals. Comparative modelling also shows that they have a similarly low power carrying capacity to organic fluids. However, they are much more likely to cover the entirety of the temperature range. It is also true that there are many more halides that have the potential to be viable heat pipe fluids which have not yet been explored as highlighted in Werner's doctoral thesis [47]. It is worth continuing to collect and database more property data on halide fluids to perform comparative studies to steer future halide compatibility testing and performance analysis.
- Although Sulphur suffers form very high liquid viscosity, studies with Sulphur/Iodine mixtures have shown some promise. While there have been very limited studies done on the mixture in the context of heat pipes, it has been seen to be compatible with Stainless Steel 304 which is a promising sign. While the comparative power carrying capacity of the mixture could not be assessed due to lack of availability of property data, it is plausible that it could outperform both halides and organic fluids on account Sulphur's marginally higher liquid thermal conductivity and enthalpy of vaporisation. The acquisition of robust Sulphur/Iodine property data should be the first port of call on assesing the fluid further.
- Other mixtures such as Sodium/Potassium seemed very promising initially, however it was quickly found that the 'geyser boiling' phenomenon makes the mixture inadequate in the medium temperature range. It is possible that experimentation with other additives could help reduce this effect, but much more research on the topic is needed. The mixture also suffers from a lack of available property data to perform comparative analysis. The exploration of further liquid metal based binary fluids could be an interesting avenue to pursue.

Clearly more work is urgently needed in this field to progress a viable solution for an intermediate temperature heat pipe. This work has aimed to identify the current status of the medium temperature research and development, consolidate key information needed to assess the viability of fluids as heat pipe fluids, estimate the most likely fluids to reach successful widespread implementation in future through theoretical analysis and suggest some key methods by which this research in this field could be accelerated.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Additinal data to the ones provided in the supplementary documents can be made available upon approval of sponsor company.

Acknowledgments

This work was made possible through the support of the Engineering and Physical Sciences Research Council (project code 1790747), the European H2020-MSCA-RISE ThermaSMART project (project code 778104) and Boyd Technologies Ashington UK Ltd. The authors would like to thank David Mullen, Elvedin Halimic and Steven Cochran at Boyd for their support.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.applthermaleng.2023.121371.

References

[1] D. Reay, P. Kew, Heat Pipes Theory, Design and Applications, 2006.
[2] M. Mochizuki, R. Sigh, T. Nguyen, Completely passive heat pipe based emergency core cooling system, in: 16th International Heat Pipe Conference (16th IHPC), 2012.
[3] C. Hoa, B. Demolder, A. Alexandre, Roadmap for developing heat pipes for ALCATEL SPACE's satellites, Appl. Therm. Eng. 23(9 SPEC) (2003) 1099–1108. 10.1016/S1359-4311(03)00039-5.
[4] G. Wang, D. Mishkinis, D. Nikanpour, Capillary heat loop technology: Space applications and recent Canadian activities, Appl. Therm. Eng. 28 (4) (2008) 284–303, https://doi.org/10.1016/j.applthermaleng.2006.02.027.
[5] P.V. Panetta, et al., NASA/GSFC nano-satellite technology development, Science (1998) 115–122.
[6] G. Canti, G.P. Celata, M. Cumo, M. Furrer, Thermal hydraulic characterization of a heat pipe with extracapillary circulation, Int. J. Therm. Sci. 41 (2) (2002) 115–123, https://doi.org/10.1016/S1290-0729(01)01289-3.
[7] R. Wrobel, D. Reay, A feasibility study of heat pipes for thermal management of electrical machines, in: ECCE 2020 - IEEE Energy Conversion Congress and Exposition, Institute of Electrical and Electronics Engineers Inc., Oct. 2020, pp. 4230–4237, https://doi.org/10.1109/ECCE44975.2020.9236391.
[8] Y. Changbao, Z. Hui, Z. Jingyang, Performance simulation analysis of composite thermal management system for hypersonic vehicle, IOP Conf. Ser. Mater. Sci. Eng. 751 (1) (2020) pp, https://doi.org/10.1088/1757-899X/751/1/012078.
[9] L. Hongpeng, L. Weiqiang, Thermal-structural analysis of the platelet heat-pipe-cooled leading edge of hypersonic vehicle, Acta Astronaut. 127 (2016) 13–19, https://doi.org/10.1016/j.actaastro.2016.05.014.
[10] R. Hay, W.G. Anderson, Water-titanium heat pipes for spacecraft fission power, in: 13th International Energy Conversion Engineering Conference, 2015, pp. 1–12.
[11] G. C. Birur, Thermal control of small spacecraft using single and two-phase fluid loops, in: International Two-Phase Thermal Control Technology Workshop, no. 1, p. 2003, 2003. <http://hdl.handle.net/2014/7668>.
[12] S. M. Cummings, R. W. Baldauff, M. A. Brown, Advanced Loop Heat Pipes For Spacecraft Central Thermal Bus Concept Technical Background of A-LHP Technology, 2002.
[13] J. Baumann, S. Rawal, Viability of loop heat pipes for space solar power applications, in: 35th AIAA Thermophysics Conference. 2001. 10.2514/6.2001-3078.
[14] A. Faghri, Heat pipes: review, opportunities and challenges, Front. Heat Pipes 5 (1) (2014) pp, https://doi.org/10.5098/fhp.5.1.
[15] S. Jafari, T. Nikolaidis, Thermal management systems for civil aircraft engines: Review, challenges and exploring the future, Appl. Sci. (Switzerland) 8 (11) (2018) 1–16, https://doi.org/10.3390/app8112044.
[16] M. Omidi, M. Farhadi, M. Jafari, A comprehensive review on double pipe heat exchangers, Appl. Therm. Eng. 110 (2017) 1075–1090, https://doi.org/10.1016/j.applthermaleng.2016.09.027.
[17] J. Jose, R. Baby, "Recent advances in loop heat pipes: A review", *IOP Conf Ser*, Mater Sci Eng 396 (1) (2018) pp, https://doi.org/10.1088/1757-899X/396/1/012060.
[18] A. Faghri, Review and advances in heat pipe science and technology, J. Heat Transfer 134 (12) (2012) 1–18, https://doi.org/10.1115/1.4007407.
[19] H.E. Ahmed, B.H. Salman, A.S. Kherbeet, M.I. Ahmed, Optimization of thermal design of heat sinks: a review, Int. J. Heat Mass Transf. 118 (2018) 129–153, https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.099.
[20] R. Wrobel, R.J. McGlen, Heat pipes in thermal management of electrical machines – a review, Therm. Sci. Eng. Prog. 26(April) (2021), 101053, https://doi.org/10.1016/j.tsep.2021.101053.
[21] J.M. Ochterbeck, Heat pipes, NASA Contractor Rep. (1975) 1181–1230.
[22] J. Jose, T. Kumar Hotta, A comprehensive review of heat pipe: its types, incorporation techniques, methods of analysis and applications, Thermal Science and Engineering Progress, vol. 42. Elsevier Ltd, Jul. 01, 2023. doi:10.1016/j.tsep.2023.101860.
[23] M. Rogowski, R. Andrzejczyk, Recent advances of selected passive heat transfer intensification methods for phase change material-based latent heat energy storage units: a review, Int. Commun. Heat Mass Transfer 144 (May 2023), https://doi.org/10.1016/j.icheatmasstransfer.2023.106795.
[24] K. Cheung, Thermal Performance and Operational Characteristics Of Loop Heat Pipe (NRL LHP), 1998.
[25] Y. Wang, G.P. Peterson, Investigation of a novel flat heat pipe, J. Heat Transfer 127 (2) (2005) 165–170, https://doi.org/10.1115/1.1842789.
[26] A. A. M. Delil, F. Mugele, Unrealised & novel thermal control issues for applications in future spacecraft, 2005.
[27] H. Jouhara, J. Milko, J. Danielewicz, M.A. Sayegh, The performance of a novel flat heat pipe based thermal and PV/T (photovoltaic and thermal systems) solar collector that can be used as an energy-active building envelope material, Energy 108 (2016) 148–154, https://doi.org/10.1016/j.energy.2015.07.063.
[28] R. S. Gaugler, Heat transfer device, 1944.
[29] Scopus.com. by Elsevier.
[30] A. Devarakonda, W.G. Anderson, Thermo-physical properties of intermediate temperature heat pipe fluids, AIP Conf. Proc. 746 (February) (2005) 179–186.
[31] J. H. Rosenfeld, An Overview of Long Duration Sodium Heat Pipe Tests, no. March 2004, pp. 140–147, 2004, 10.1063/1.1649568.
[32] W. G. Anderson, J. J. Bland, High temperature loop heat pipe, 1995.
[33] A. Devarakonda, J. K. Olminsky, An evaluation of halides and other substances as potential heat pipe fluids, Collection of Technical Papers - 2nd International Energy Conversion Engineering Conference, vol. 1. pp. 471–477, 2004.
[34] M. Groll, O. Brost, D. Heine, T. Spendel, Heat transfer, vapour liquid flow interations and material compatibility in two-phase thermosyphons, Energy Conservation in Industry: Combustion, Heat Recovery and Rakine Cycle Machines, 1982.
[35] W. G. Anderson, W. Bienert, Loop heat pipe radiator trade study for the 300-550 K temperature range, 2005.
[36] J.H. Rosenfeld, N.J. Gernert, Life test results for water heat pipes operating at 200 °C to 300 °C, AIP Conf. Proc. 969 (2008) 123–130, https://doi.org/10.1063/1.2844957.
[37] E. W. Saaski, Two Phase working fluids for the temperature range 100°C to 350°C, 1977.
[38] R.S. Reid, J.T. Sena, A.L. Martinez, Heat-pipe development for advanced energy transport concepts final report covering the period, Los Alamos National Lab no. September (2001).
[39] J.H. Rosenfeld, N.J. Gernert, Advances in high temperature titanium-water heat pipe technology, AIP Conf. Proc. 880 (2007) 129–136, https://doi.org/10.1063/1.2437449.
[40] R.S. Reid, M.A. Merrigan, J.T. Sena, Review of liquid metal heat pipe work at Los Alamos, AIP Conf. Proc. 999 (May) (1991) 999–1008, https://doi.org/10.1063/1.40058.
[41] G.M. Grover, J.E. Kemme, E.S. Keddy, Advances in heat pipe technology, J. Chem. Inf. Model. 53 (9) (2013) 1689–1699, https://doi.org/10.1017/CBO9781107415324.004.
[42] E. W. Saaski, J. H. Hartl, High-performance heat pipes for heat recovery applications, 1980.
[43] Y. Feng, Y. Ji, M. Wu, X. Yang, Y. Li, Z. Liu, Experimental investigation on diamond-sodium potassium alloy high- temperature oscillating heat pipe, J. Eng. Thermophys. (2022).
[44] P. Wallin, Heat Pipe, Selection of Working Fluid, 2012, pp. 1–7.
[45] J. H. Rosenfeld, Advances in High Temperature Ti-Water Heat Pipe Technology. pdf.
[46] T. C. Werner, Challenges in operating heat pipes above 350°C, 2019. <http://www.hexag.org/news/36/thomas_werner.pdf> (Accessed Jul. 10, 2023).
[47] T. C. Werner, Investigation of Novel Analytical Tools and Experimental Methods for the Development of Intermediate Temperature Heat Pipes.
[48] P. Szymanski, D. Mikielewicz, Challenges in operating and testing loop heat pipes in 500-700 K temperature ranges, Arch. Thermodyn. 43(2) (2022) 61–73, 10.24425/ather.2022.141978.
[49] H. Jouhara, N. Khordehgah, S. Almahmoud, B. Delpech, A. Chauhan, S.A. Tassou, Waste heat recovery technologies and applications, Therm. Sci. Eng. Prog. 6 (April) (2018) 268–289, https://doi.org/10.1016/j.tsep.2018.04.017.
[50] J. Hammoud, S. Dudley, N. Apte, Use of heat pipe technology for multi media thermal management, SAE Techn. Papers 724 (2006), https://doi.org/10.4271/2006-01-0482.
[51] J. Wen, Thermal resistance modeling of oscillating heat pipes filled with acetone by using artificial neural network, J. Therm. Anal. Calorim. 144 (5) (2021) 1873–1881, https://doi.org/10.1007/s10973-020-10536-x.
[52] S.N. Li, Z.T. Liang, B.H. Yan, A medium temperature heat pipe cooled reactor, Ann. Nucl. Energy 172 (2022), https://doi.org/10.1016/j.anucene.2022.109068.
[53] P. A. Anil, Compound Parabolic Concentrator, 2018.
[54] U.R. Singh, A. Kumar, Review on solar stirling engine: development and performance, Therm. Sci. Eng. Prog. 8 (July) (2018) 244–256, https://doi.org/10.1016/j.tsep.2018.08.016.
[55] G. Jing-hu, L. Yong, W. Jun, P. Lund, Performance optimization of larger-aperture parabolic trough concentrator solar power station using multi-stage heating technology, Energy 268 (2023), https://doi.org/10.1016/j.energy.2023.126640.
[56] M. Tawalbeh, H.A. Khan, A. Al-Othman, F. Almomani, S. Ajith, A comprehensive review on the recent advances in materials for thermal energy storage applications, Int. J. Thermofluids 18 (2023), 100326, https://doi.org/10.1016/j.ijft.2023.100326.

[57] R.P. Merchán, M.J. Santos, A. Medina, A. Calvo Hernández, High temperature central tower plants for concentrated solar power: 2021 overview, Renew. Sustain. Energy Rev. 155 (2022), 111828, https://doi.org/10.1016/j.rser.2021.111828.

[58] R. Senthil, et al., A holistic review on the integration of heat pipes in solar thermal and photovoltaic systems, Sol. Energy 227 (June) (2021) 577–605, https://doi.org/10.1016/j.solener.2021.09.036.

[59] M. Aramesh, B. Shabani, Experimental evaluation of a self storage integrated evacuated tube solar thermal collector, J. Energy Storage 62 (Jun. 2023), https://doi.org/10.1016/j.est.2023.106920.

[60] P.V. Chilbule, L.P. Dhole, Heat pipe integrated solar thermal systems and applications: a review, Mater. Today Proc. 60 (2022) 1491–1496, https://doi.org/10.1016/j.matpr.2021.11.563.

[61] R. Xu, J. Chen, X. Zhang, R. Wang, S. Xu, Heat leakage numerical investigation of a compound parabolic concentrator-pulsating heat pipe solar collector, J. Therm. Sci. 31 (5) (2022) 1318–1326, https://doi.org/10.1007/s11630-020-1293-3.

[62] A. Kumar, Z. Said, E. Bellos, An up-to-date review on evacuated tube solar collectors, J. Therm. Anal. Calorim. vol. 145, no. 6. Springer Science and Business Media B.V., pp. 2873–2889, Sep. 01, 2021. 10.1007/s10973-020-09953-9.

[63] Z. Wang, Y. Diao, Y. Zhao, C. Chen, T. Wang, L. Liang, Visualization experiment and numerical study of latent heat storage unit using micro-heat pipe arrays: melting process, Energy 246 (2022), https://doi.org/10.1016/j.energy.2022.123443.

[64] S. Kraemer, TEXEL Explores US Market for 2-Cent Thermal Energy Storage in Metal Hydrides, 2020. <https://www.solarpaces.org/texel-explores-us-market-for-2-cent-thermal-energy-storage-in-metal-hydrides/>.

[65] P. White, Texel offers another candidate for a hydrogen based battery, 2021. <https://rethinkresearch.biz/articles/texel-offers-another-candidate-for-a-hydrogen-based-battery/> (Accessed Jun. 24, 2023).

[66] S. Simmonds, R. Corbishley, J. Hughes, G. Taylor, The Development of the MAHLE 25kWe Solar Heated Stirling Engine Topics: Thermodynamic & Mechanical Simulation, Engine Testing, p. 738100.

[67] Y.L. He, Y. Qiu, K. Wang, F. Yuan, W.Q. Wang, Perspective of concentrating solar power, Energy 198 (2020), https://doi.org/10.1016/j.energy.2020.117373.

[68] C. Forman, I.K. Muritala, R. Pardemann, B. Meyer, Estimating the global waste heat potential, Renew. Sustain. Energy Rev. 57 (2016) 1568–1579, https://doi.org/10.1016/j.rser.2015.12.192.

[69] R.S. Vizitiu, A. Burlacu, C. Abid, M. Verdes, M.C. Balan, M. Branoaea, Experimental and numerical study of thermal performance of an innovative waste heat recovery system, Appl. Sci. (Switzerland) 11 (23) (2021), https://doi.org/10.3390/app112311542.

[70] M. Sakthi Priya, D. Sakthivadivel, Experimental investigation on the thermal performance of a novel thermosyphon heat pipe with truncated cone for heat recovery systems, Energy Convers. Manag. 276 (2023), https://doi.org/10.1016/j.enconman.2022.116522.

[71] H. Jouhara, et al., Waste heat recovery solution based on a heat pipe heat exchanger for the aluminium die casting industry, Energy 266 (2023), https://doi.org/10.1016/j.energy.2022.126459.

[72] H. Jouhara, et al., Investigation on a full-scale heat pipe heat exchanger in the ceramics industry for waste heat recovery, Energy 223 (2021), 120037, https://doi.org/10.1016/j.energy.2021.120037.

[73] L. Yodrak, S. Rittidech, N. Poomsa-ad, Waste heat recovery by heat pipe air-preheater to energy thrift from the furnace in a hot forging process, Am. J. Appl. Sci. 7 (5) (2010) 675–681, https://doi.org/10.3844/ajassp.2010.675.681.

[74] J.H. You, et al., European divertor target concepts for DEMO: design rationales and high heat flux performance, Nucl. Mater. Energy 16 (April) (2018) 1–11, https://doi.org/10.1016/j.nme.2018.05.012.

[75] B.H. Yan, C. Wang, L.G. Li, The technology of micro heat pipe cooled reactor: a review, Ann. Nucl. Energy 135 (2020), https://doi.org/10.1016/j.anucene.2019.106948.

[76] B. Zohuri, S. Lam, C. Forsberg, Heat-pipe heat exchangers for salt-cooled fission and fusion reactors to avoid salt freezing and control tritium: a review, Nucl. Technol. 206(11). Bellwether Publishing, Ltd., pp. 1642–1658, Nov. 01, 2020. 10.1080/00295450.2019.1681222.

[77] M. Coutinho et al., A review on the recent developments in thermal management systems for hybrid-electric aircraft, Appl. Therm. Eng. vol. 227. Elsevier Ltd, Jun. 05, 2023. 10.1016/j.applthermaleng.2023.120427.

[78] R. Fusaro, D. Ferretto, N. Viola, R. Scigliano, V. De Simone, M. Marini, Liquid Metals Heat-Pipe solution for hypersonic air-intake leading edge: Conceptual design, numerical analysis and verification, Acta Astronaut. 197 (2022) 336–352, https://doi.org/10.1016/j.actaastro.2022.05.034.

[79] P. M. Dussinger, W. G. Anderson, E. T. Sunada, Design and testing of titanium/cesium and titanium/potassium heat pipes, in: Collection of Technical Papers - 3rd International Energy Conversion Engineering Conference, vol. 2, pp. 1088–1096, 2005.

[80] M. Groll, Heat pipe research and development in western Europe, Heat Recovery Syst. CHP 9 (1) (1989) 19–66, https://doi.org/10.1016/0890-4332(89)90139-7.

[81] W.G. Anderson, Evaluation of heat pipes in the temperature range of 450 to 700 K, AIP Conf. Proc. 746 (2005) 171–178, https://doi.org/10.1063/1.1867132.

[82] W. G. Anderson, Intermediate temperature fluids for heat pipes and loop heat pipes, in: Collection of Technical Papers - 5th International Energy Conversion Engineering Conference, vol. 2, no. June, pp. 1147–1164, 2007.

[83] J. E. Deverall, Mercury as a heat pipe fluid, 1970.

[84] D. D. Kenney, K. T. Feldman, K. T. Jr. Feldman, Heat pipe life tests at temperatures up to 400 C, 1978.

[85] E.W. Saaski, P.C. Owzarski, Two-phase working fluids for the temperature range 50° to 350°C, Heat Transfer Therm. Control Syst. (1978) 63–79, https://doi.org/10.2514/5.9781600865343.0063.0079.

[86] I. E. Locci, A. Devarakonda, E. H. Copland, J. K. Olminsky, Analytical and experimental thermo-chemical compatibility study of potential heat pipe materials, in: Collection of Technical Papers - 3rd International Energy Conversion Engineering Conference, vol. 2, no. August, pp. 1285–1292, 2005, 10.2514/6.2005-5666.

[87] H. Jouhara, A.J. Robinson, An experimental study of small-diameter wickless heat pipes operating in the temperature range 200c to 450c, Heat Transfer Eng. 30 (13) (2009) 1041–1048, https://doi.org/10.1080/01457630902921113.

[88] E.W. Saaski, J.H. Hartl, Two-phase working fluids for the temperature range 50° to 350°C - Phase II, NASA Lewis Research Centre 2 (1980).

[89] A. Basiulis, R. C. Prager, T. R. Lamp, Compatibility and Reliability of Heat Pipe Materials, 1975, pp. 357–372. 10.2514/6.1975-660.

[90] W. G. Anderson, D. Sarraf, P. M. Dussinger, T. Stern, J. Barth, Development of a high temperature water heat pipe radiator, in: Collection of Technical Papers - 3rd International Energy Conversion Engineering Conference, 2005, pp. 1105–1113. 10.2514/6.2005-5633.

[91] T. J. Sena, M. A. Merrigan, Niobium-1% Zirconium/Potassium life-test heat pipe design and testing, in: 28th Aerospace Sciences Meeting, 1990, 1990.

[92] J. H. Rosenfeld, I. E. Locci, J. L. Sanzi, D. R. Hull, S. M. Geng, Post test analysis of a ten year sodium heat pipe life test, Nuclear and Emerging Technologies for Space 2011, NETS-2011, pp. 392–399, 2011.

[93] W.G. Anderson, P.M. Dussinger, D. Sarraf, High temperature water heat pipe life tests, AIP Conf. Proc. 813 (2006) 100–107, https://doi.org/10.1063/1.2169185.

[94] L. R. Grzyll, D. D. Back, C. Ramos, N. A. Samad, Characterization and testing of novel two-phase working fluids for spacecraft thermal management systems operating between 300°C and 400°C, 1994.

[95] L. R. Grzyll, Investigation of heat pipe working fluids for thermal control of the sodium/sulfur battery, in: Proceedings of the Intersociety Energy Conversion Engineering Conference, 1991, pp. 390–394.

[96] A. M. Groll, D. Heine, T. Spendel, M. Groll, Heat transfer, vapour-liquid flow interaction and materials compatibility in two-phase thermosyphons, 1981.

[97] T. Yamamoto, K. Nagata, M. Katsuta, Y. Ikeda, Experimental study of mercury heat pipe, National Institute for Resources and Environment (1984) 39–46.

[98] D. Jacobson, Analytical and experimental investigations of sodium heat pipes and thermral energy storage systems, 1982.

[99] T. Wenyu, Z. Kai, Experimental study on start-up performance and isothermal performance of N-methylpyrrolidone heat pipe, 2020.

[100] G. Yuxiang, C. Hongxia, Y. Dazhong, L. Linhan, W. Yiran, J. Yang, Startup and heat transfer performance of medium temeprature cesium heat pipe, 2021.

[101] H.X. Chen, Y.X. Guo, D.Z. Yuan, Y. Ji, Experimental study on frozen startup and heat transfer characteristics of a cesium heat pipe under horizontal state, Int. J. Heat Mass Transf. 183 (2022), https://doi.org/10.1016/j.ijheatmasstransfer.2021.122105.

[102] W.G. Anderson, S. Tamanna, C. Tarau, J.R. Hartenstine, D.L. Ellis, Intermediate temperature heat pipe life tests and analyses, in: 43rd International Conference on Environmental Systems, 2013, pp. 1–23.

[103] W. G. Anderson, T. Calin, D. Ellis, Y. Zhang, Heat Pipes Design, Applications And Technology Chapter 7: Intermediate Temperature Heat Pipe Working Fluids, 2018.

[104] C. Tarau, D. B. Sarraf, I. E. Locci, W. G. Anderson, Intermediate temperature fluids life tests - theory, AIP Conf Proc, vol. 880, no. May 2017, pp. 137–146, 2007, 10.1063/1.2437450.

[105] W. G. Anderson, Sodium-potassium heat pipe, 1993.

[106] W.G. Anderson, R.W. Bonner, P.M. Dussinger, J.R. Hartenstine, D.B. Sarraf, I. E. Locci, Intermediate temperature fluids life tests - experiments, 5th International Energy Conversion Eng. Conf. 2 (June) (2007) 926–941, https://doi.org/10.2514/6.2007-4808.

[107] J.H. Rosenfeld, G.Y. Eastman, J.E. Lindemuth, Sulfur heat pipes for 600 K space heat rejection systems, AIP Conf. Proc. 1170 (1992) (1992) 1170–1176, https://doi.org/10.1063/1.41780.

[108] W.G. Anderson, Evaluation of heat pipe working fluids in the temperature range 450 to 700 K, AIP Conf. Proc. 20 (2004) (2004) 20–27, https://doi.org/10.1063/1.1649553.

[109] H. Guo, Q. Guo, X.K. Yan, F. Ye, C.F. Ma, Experimental investigation on heat transfer performance of high-temperature thermosyphon charged with sodium-potassium alloy, Appl. Therm. Eng. 139 (April) (2018) 402–408, https://doi.org/10.1016/j.applthermaleng.2018.04.139.

[110] Y. Ji, et al., An experimental investigation on the heat transfer performance of a liquid metal high-temperature oscillating heat pipe, Int. J. Heat Mass Transf 149 (2020), 119198, https://doi.org/10.1016/j.ijheatmasstransfer.2019.119198.

[111] L. L. Vasil'ev, G. M. Volokhov, A. S. Gigevich, M. I. Rabetskii, Heat pipes based on naphthalene, J. Eng. Phys. 54(6) (1988) 623–626, 10.1007/BF01102648.

[112] W. G. Anderson, J. H. Rosenfeld, A. Devarakonda, Y. Mi, Evaluation of heat pipes working fluid in the temperature range 450 to 700 K, 2004.

[113] B. Orra, R. Singh, A. Akbarzadeh, M. Mochizuki, Operating characteristics of naphthalene heat pipes, Front. Heat Mass Transfer 13 (2019), https://doi.org/10.5098/hmt.13.8.

[114] T.C. Werner, Y. Yan, D. Mullen, E. Halimic, Experimental analysis of a high temperature water heat pipe for thermal storage applications, Therm. Sci. Eng. Prog. 19 (2020), https://doi.org/10.1016/j.tsep.2020.100564.

[115] H.X. Chen, Y.X. Guo, D.Z. Yuan, Y. Ji, Thermal performance of a medium temperature cesium heat pipe at different inclination angles, Int. Commun. Heat

Mass Transfer 138 (2022), https://doi.org/10.1016/j.icheatmasstransfer.2022.106363.
[116] L.R. Grzyll, Investigation of heat pipe working fluids for thermal control of the sodium/sulfur battery, in: Proceedings of the Intersociety Energy Conversion Engineering Conference, 1991, pp. 390–394.
[117] F. Polasek, P. Stulc, Heat pipes for the temperature range from 200°C to 600°C, Int. Heat Pipe Conf. 2 (1976) 711–732, https://doi.org/10.1111/j.1536-7150.1978.tb02790.x.
[118] P.D. Dunn, D.A. Reay, The heat pipe, Phys. Technol. 4 (3) (1973) 187–201, https://doi.org/10.1088/0305-4624/4/3/I01.
[119] Unknown, BS EN 828 Adhesives - Wettability - Determination by measurement of contact angle and surface free energy of solid surface, 2013.
[120] Y. Yun and T. Lee, Contact Angle and Wetting Properties, vol. 51, no. 1. 2013. 10.1007/978-3-642-34243-1.
[121] C. L. Yaws, Chemical Properties Handbook: Physical, Thermodynamic, Environmental, Transport, Safety, and Health Related Properties for Organic and Inorganic Chemicals, McGrawHill handbooks. p. 779, 1999. [Online]. <http://www.knovel.com/knovel2/Toc.jsp?BookID=49>.
[122] I.B. Johns, E.A. McElkill, J.O. Smith, Thermal Stability of organic compounds, Clay-Contain. Polym. Nanocompos. 44 (1962) 243–261, https://doi.org/10.1016/b978-0-444-59437-2.00007-7.
[123] A. Devarakonda, D. Xiong, D.E. Beach, Intermediate temperature water heat pipe tests, in: AIP Conf Proc, vol. 746, no. March 2005, pp. 158–163, 2005, 10.1063/1.1867130.
[124] M. Park, J.H. Boo, Thermal performance of a heat pipe for medium-temperature thermal storage system, in: 10th International Heat Pipe Symposium, 2011, pp. 13–18.
[125] M. S. El-Genk, J.-M. P. Tournier, Uses of liquid-metal and water heat pipes in space reactor power systems, Front. Heat Pipes 2(1) (2011), 10.5098/fhp.v2.1.3002.
[126] S. Benson, W. Sidney, The foundations of chemical kinetics, Division of Chemical Education (1960).
[127] X. Meng, G. Zuo, Z. Sun, W. Xu, M. Huang, C. Xu, Compatibility of molybdenum, tungsten, and 304 stainless steel in static liquid lithium under high vacuum, Plasma Phys. Rep. 44 (7) (2018) 671–677, https://doi.org/10.1134/S1063780X18070036.