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Material Selection for Micro Channel Heat Exchangers for Industrial Waste Heat Recovery

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***Abstract*—** The aim of this paper is to provide the software-based materials selection approach for the micro channel heat exchanger for high-temperature industrial waste heat recovery. Industrial heat processing and heat recovery places increasing demand for material performance in extreme conditions. These extreme conditions accelerate the material's degradation in turn leading to performance and efficiency reduction. Therefore the development of new compatible materials demand material qualification for the miniaturized technology to function over a long period of time with full efficiency. This paper proposes methodology for the material identification and selecting appropriate material for the micro channel heat exchanger to recover high-temperature (>500 ℃) industrial waste heat. Thermally stable materials such as aluminum nitride, silicon carbide, alumina, tungsten carbide, tungsten alloys, and nickel and TZM alloys were observed to perform exceptionally well in extreme condition. Thus silicon carbide, aluminum nitride and molybdenum TZM alloys were selected as the most promising materials for micro channel heat exchanger recover high-temperature (500-750 ℃) waste heat from different industries.

***Keywords*—** Cambridge Engineering Selector, Micro channel heat exchanger, Materials selection

Abbreviations and Nomenclatures

MCHE	Micro Channel Heat Exchanger
CES	Cambridge Engineering Selector
WHR	Waste Heat Recovery
TZM	Molybdenum Titanium Zirconium
Nu	Nusselt number
h_c	Convection heat coefficient
D_h	Hydraulic diameter (mm)
q	Heat transfer rate
ΔT	Temperature difference
α	Coefficient of expansion
k	Thermal conductivity
Sy	Yield Strength

I. INTRODUCTION

Micro channel heat exchanger is an advanced field full of challenges. The compact design, higher heat transfer capabilities, lower weight, and cost expand MCHE applications in heating, ventilation, and air conditioning, petroleum, and chemical processing engineering, automotive, electronic equipment and waste heat recovery from various heat processing industries. Micro channel heat exchanger recovers waste heat from various industries including furnace heat and exhaust from steam boiler, gas turbine, and heat treatment furnaces. The exhaust temperature varies from a lower heat source such as gas-fired boiler exhaust to high nickel refining furnace. The MCHE material' s exposure to high temperature (>500℃) exhaust/ waste heat imposes a challenge of thermal degradation. The degradation might be caused by corrosion and erosion due to metal oxides and impure particle reacts with material in a high-temperature harsh environment. Based on functional and design requirements, possible candidates will be evaluated for overall performance and cost of MCHE applications. Given the growing number of materials available today, finding suitable material is a time-consuming process. The selection of low cost and high-performance materials for MCHE is vital to achieving optimum waste heat recovery. The essential criteria for suitable materials involve higher heat transfer, lower thermal expansion, and thermal stability at harsh environments. The high heat transfer coefficient and greater cross-sectional area to volume ratio are the key advantages of MCHE over conventional heat exchanger. The heat transfer flowing through working fluid inside the micro channel diameter (< 1mm) can be described by the MCHE basic equation as follows.

$$hc = Nu\ k/Dh \qquad (1)$$

Tuckerman and Pease et al. 1981 [1] Presented the idea of heat exchange in micro channel by receiving the bloodstream flow concept in human supply routes. The increase in convection heat transfer results from the decrease in channel dimension shown in equation 1. The limited space heat dissipation problems were given a boost in the electronics industry by the introduction of micro channel's concept. This revolutionary concept explored different perspective for researchers. Dixit and Ghosh et al. 2015 [2] Reviewed the micro channel's fabrication hurdle with conventional technology led to the development of non-conventional techniques. Micro channels currently used for high heat processing industry instead of removal of dissipated heat. The main hurdle for commercialization of micro channels is the higher fabrication cost and non-conventional methods. The laminar flow conventional theory validation about constant Nusselt number was proved by Tuckerman and Pease et al. 1981 [1]. The silicon-based micro channel was tested with distilled water as a working fluid and showed high heat dissipation about 790 W/cm2. The hydraulic diameter reduction significantly improves the convection heat transfer for a specific fluid. The design parameters play key role in heat transfer optimization apart from dimensional parameters. Knight, Hall et al. 1992 [3], Lee, Kim et al. 2005 [4], and Riera, Barrau et al. 2015 [5] studied the importance of design constraint in micro channel's performance optimization. Harms, Kazmierczak et al. 1999 [6] Proposed the macro scale law for micro channels and suggested the single and multiple channels can be related by classical correlation but failed in the experimental investigation due to Nusselt number deviation for the lower value of Reynolds number.

Mohammed, Bhaskaran et al. 2011 [7] Studied correlation of Reynolds number in micro channels with Nusselt number for accuracy and the proposed threshold value (1.2 mm) of hydraulic diameter. Segre and Silberberg et al. 1962 [8] studied and determined the constant value of Poiseuille number for laminar flow within stainless steel and fused silica micro channels with water, methanol, and isopropanol as a working fluid. Khan and Fartaj et al. 2011 [9] published their detail on micro channel heat exchanger and was potentially introduced by Peng and Peterson et al. 1996 [10]. The author proposed the Joule Thomson effect applications inside the channels. Review work on cross-flow micro channel heat exchanger's fabrication and fluid dynamics were done by many researchers such as Wu and Cheng et al. 2003 [11], Harms, Kazmierczak et al. 1999 [6] and Jiang, Fan et al. 2001 [12].

A. *Applications*

Westphalen and Koszalinski et al. 1999 [13] and Kandlikar et al. 2005 [14] illustrated the micro channel heat exchanger's application in HVAC systems as energy saver defined by less refrigerant consumption and deliver higher overall efficiency. Apart from the higher fabrication's cost, MCHE gained importance in various refrigeration applications. The MCHE applications in air conditioning field, heat pump, and vapor compression refrigeration's system proposed and investigated by Pettersen, Hafner et al. 1998 [15], Han, Liu et al. 2012 [16] and Leland and Ponnappan et al. 2001 [17]. The smaller size and lower weight along with micro channel heat exchanger's improvement in heat transfer performance have made compulsory choice in space applications studied by Harris, Despa et al. 2000 [18], gas turbines Min, Jeong et al. 2009 [19] and waste heat recovery Sommers, Wang et al. 2010 [20], Meng, Wang et al. 2016 [21]. The other applications involve gas liquefaction plant Baek, Kim et al. 2010 [22] and heat processing industries Thonon and Breuil 2001 [23]. Micro channel heat exchangers became an integral part of electronic circuits and devices cooling Kandlikar, Garimella et al. 2005 [24], Walpole and Missaggia 1992 [25]. MCHE have been employed to fuel and solar cell systems Reuse, Renken et al. 2004 [26], Li, Flamant et al. 2011 [27] and for biomedical applications by Silvestri and Schena et al. 2012 [28].

B. *Material*

Materials play an important role in mechanical design. Numerous research has been done on design, fabrication, applications and heat transfer characterization through the micro channels. The aforementioned literature on different materials for MCHE has been summarized in the material section. Although, Silicon and Copper are the two common materials for MCHE. Subsequently, the researcher investigated the fluid flow through single-phase and two-phase micro channels. This paper explores the methodology of identifying materials for micro channel heat exchangers. The mathematical model developed validate the experimentally measured value of temperature distribution and pressure drops within the aluminum-based micro channel heat exchanger. The experimental procedure was arranged for copper-based MCHE by Dixit and Ghosh et al. 2015 [2]. The manufacturing of copper MCHE and investigations conducted on varying heat flux value by Qu and Mudawar et al. 2002 [29] concluded the temperature profile correlation for non-uniform heat flux. Liu, Xiao et al. 2016 [30] Concluded that decrease in saturation temperature and rise in vapor eminence and bulk flux significantly increase the heat transfer coefficient and pressure drop inside the square shape copper mini channels. Del Col, Bortolin et al. 2011 [31] Did a similar study on square shape micro channels but observed no significant improvement in heat transfer coefficient regardless of similar test conditions. Brandner, Anurjew et al. 2006 [32] Analyzed the various parameters to enhance the heat transfer coefficient of copper made micro channel heat exchangers. The author concluded the shortest distance between the heat source and sink, the decrease in dimensional characterization (<100 µm) and changing the laminar flow regime to three-dimensional array increase the heat transfer coefficient. David, Miler et al. 2011 [33] Designed and conducted an experimental investigation on copper made parallel flow two-vapor phase MCHE. The two-phase vapor included a non-venting heat exchanger and vapor-separation version reduced the pressure drop for lower substrate temperature.

Bronze made MCHE were investigated by Kan, Ipek et al. 2015 [34] for varying heat flux and channel angles in order to enhance the heat transfer coefficient. The study concluded the channel angle 30o and with two-phase fluid input temperature, 60 ℃ for hot and 15 ℃ for cold give maximum heat transfer. Lee, Kim et al. 2005 [35], Shen, Xu et al. 2006 [36] and Park, Peng and Punch et al. 1995, 1996 [37. 38] studied silicon MCHE experimentally for pressure drop and convection mode of heat transfer and observed the laminar Nusselt number direct relation with lesser Reynolds number. The geometric parameter and surface structure altered for higher Reynolds numbers. Plexiglass and glasses micro channel heat exchangers were investigated by Pramod Chamarthy et al. 2010 [39] and developed a laser-induced method for temperature measurements. T-junction between hot and cold fluid mixing demonstrated based on both temperature-dependent and independent dies made of Rhodamine (RhB, 10). Peiyi Wu, Little et al. 1984 [40] measured gas flow through silicon and glass micro channel heat sink for refrigeration purpose and concluded the effective heat transfer due to the asymmetrical roughness and variation in wall temperature.

C. 1.3 CES Based Material Selection

Sameer et al. 2012 [41] used CES software approach for selecting the phase changing materials for high temperature applications. The optimization of thermal energy storage with multi-objective to identify phase changing materials for thermal energy storage. The phase changing materials considered for high-temperature (400-750℃) steam investigation were metal and their eutectics such as 60Al-34Mg-6Zn and 88Al-22Si. Thermal conductivity, environmental performance, and heat of fusion were the few attributes upon which selection of phase changing material was made. 88Al-22Si was selected as a most promising material for latent heat energy storages compared to the traditional molten salt. Camila et al. 2015 [42] generated phase changing material database for the selection of PCM at phase temperature ranges from -50℃ to 150℃ using CES selector. The investigation led to the classification of PCM including commercial and non- commercial list.

Shanian et al. 2004 [43] utilized the CES software approached to select material on the basis of multiple decision making attributes. The cost of production along with other attributes for engineering applications were considered for the ranking of the materials from the best to worst one. The case study done on non-heat treatable cylinder materials for covering worked under static load and carried efficiency closer to the room temperature. Materials were ranked based on both cost inclusion and exclusion.

II. MATERIAL SELECTION METHODOLOGY

Granta Design Selector (CES) package by MA. Ashby et al. 2009 [44] is used for the selection of suitable materials for MCHE. The CES selector considers various inputs for design methodology such as thermal, mechanical and chemical stability, costing and optimization of the most suitable outcome. The MCHE material can be exposed to the passive atmosphere for a prolonged period without substantial problems, such as thermal degradation due to corrosion and erosion, phase and chemical changes, loss of strength and other assets for which material propose to custom. The highest temperature in the inert atmosphere to which material is exposed is referred to service temperature. The necessary attributes of materials for high-temperature waste heat recovery MCHE applications are given in Table 1.

Table 1. Desirable Properties for MCHE Materials

Attributes	Desirable characteristics
Thermal properties	Extensive thermal stability (T> 500 ℃), High heat capacities, high thermal conductivity
Organic properties	Long term chemical stability, high corrosion resistance, non-toxic and no chemical decompositions.
Mechanical properties	Low thermal expansion coefficient, high fracture toughness and mechanical stability
Economic and Environmental propertied	Cheaper and low cost of fabrication, lower energy requirement and CO_2 footprint

For heat processing Industries, within the operating temperature, the thermal properties of the designated materials are important comprises thermal conductivity, thermal stability, heat capacities, thermal expansion, and corrosion resistance. CES classified the material's universe into six basics categories as polymers, ceramics, elastomers, glasses, metals and composites/hybrids. Thermal and chemical stability along with high service temperature was considered as the primary requirement. Based on the specification and desirable properties (Table 1), primary selection identified ceramics and metals as promising materials for micro channel heat exchangers. The CES generated material's properties chart in Figure 1 shows a variation of service temperature with melting points of ceramics and metals/alloys families. Only common materials are named for the clear presentation in Fig. 1. For MCHE applications in industrial waste heat recovery considered here, the materials should have higher service temperature (> 500 ℃) and not undergo any thermal failure that might involve phase and chemical changes, corrosion, etc. Materials like concrete, aluminum, magnesium, and titanium alloys can decompose or spall below 450 ℃ and hence cannot be used for MCHE waste heat recovery applications. Alumina, silicon and tungsten carbide, tungsten alloys, and aluminum nitrides are, however, proper candidates for high-hotness above 500 ℃ MCHE uses shown in Figure 1. Material like Molybdenum, titanium, zirconium (TZM) alloy is also a candidate for high-temperature applications.

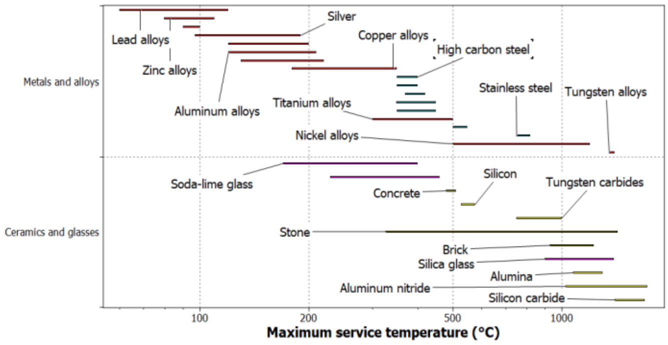

Figure 1. Illustrates the variation of ceramics and metal alloys plotted on ordinate against the maximum service temperature (℃) on abscissa.

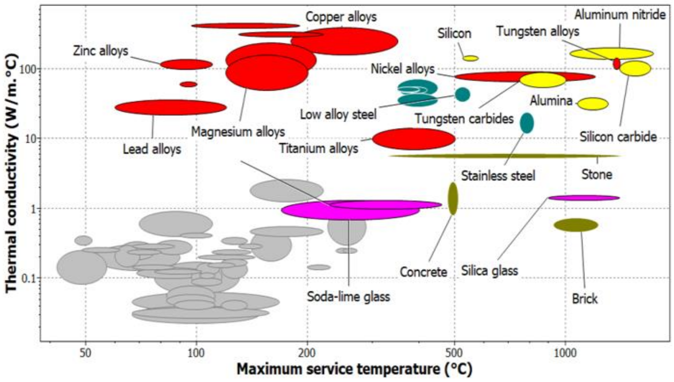

Figure 2. Illustrates the effect of maximum service temperature (℃) plotted on ordinate against the different material' s thermal conductivity (W/m. ℃) on abscissa.

The material's ability to conduct heat per unit time per unit area through solid material per degree rise in temperature is plotted on the horizontal axis against the maximum service temperature in Fig. 2. Ceramics such as silicon carbide, aluminum nitride, tungsten carbide and alumina on the top right shows higher thermal conductivity above 500 ℃. Nickel alloys and stainless steel shows greater compatibility compared to other metals and alloys.

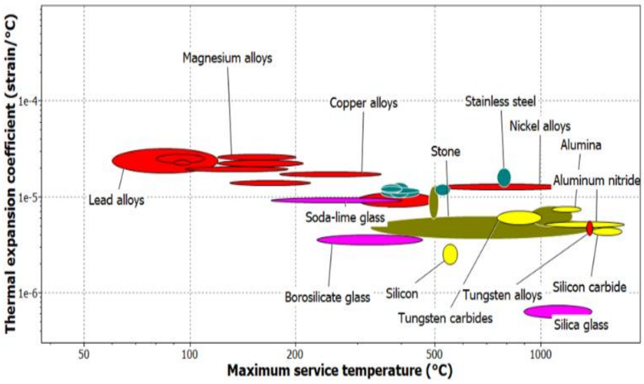

Figure 3. The effect of maximum service temperature (℃) plotted on the ordinate against the thermal expansion coefficient (starin/℃) of different available materials on abscissa.

The material's expansion per degree rise in temperature plotted on the horizontal axis against the maximum service temperature on the vertical axis illustrated in Fig. 3. The ceramic materials like silicon and tungsten carbide, alumina, aluminum nitride and metal ' s alloy such as nickel and tungsten alloys shown on the top left in Fig.3.are the compatible candidates for above 500 ℃ temperature applications with lower thermal expansion coefficient.

Figure 4 compares the fracture toughness (resistance to crack propagation) of materials on vertical axis against maximum service temperature on horizontal axis. The higher fracture toughness of ceramics and metals alloys such as alumina, aluminum nitride, silicon carbide, tungsten carbide, tungsten and nickel alloy shown on the right side of the chart describes the compatibility of these materials. The inverse plot of fracture toughness represents that materials at the lower right bottom had the highest fracture toughness. Other materials (upper left-hand side of Figure 4) might be prone to failure due to repeated thermal cycle.

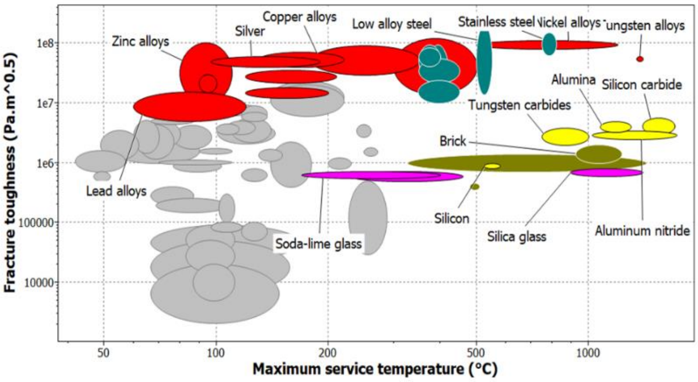

Figure 4. The effect of maximum service temperature (℃) on fracture toughness of various materials.

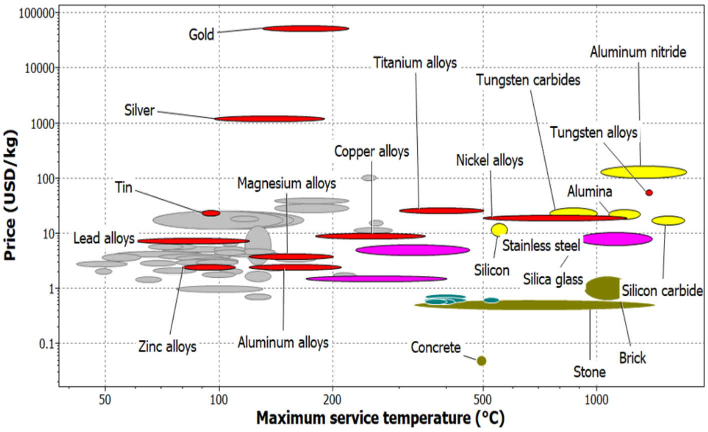

Figure 5. Illustrates the maximum service temperature (℃) materials such as ceramics and metals plotted on ordinate against the Price (USD/kg) on abscissa.

The maximum service temperature plotted against the cost of the materials shown in Fig.5. The CES graph shows the bulk materials price per unit mass. The silicon carbide and alumina are the cheapest ceramics compared to tungsten carbide and aluminum nitride, however, metal alloys such as tungsten alloy are much costlier than nickel and copper alloys. The overall analysis is done so far concluded that the ceramics such as aluminum nitride, silicon carbide, alumina and tungsten carbide and metal alloys such as tungsten, nickel and molybdenum zirconium and titanium alloy are the acceptable combination of materials for micro channel heat exchanger high-temperature waste heat recovery applications.

III. PERFORMANCE MATRICES

The performance equation contains material properties known as material indices. The material indices is a mathematical expression which relates performance with various material's properties. Micro channel heat exchanger served maximizing heat transmission to the working fluid (maximize heat flux) by reducing the hydraulic diameter of the channels given as follows.

$$hc = Nu\,K/Dh \quad (1)$$

According to the Fourier's law, heat transfer (Conduction) can be expressed as

$$q. = -k\,A\,\Delta T/\Delta t \quad (2)$$

The stresses due to internal pressure drop inside the channel can be expressed as follows.

$$\sigma = pi.r/t \quad (3)$$

The material indices for MCHE derived from above equations can be written as follows

$M1 = k\,\sigma$,

The thermal deformation that results from thermal stresses due to the exposure to high-temperature must be resisted by the materials. The thermal deformation occurs due to the temperature difference can be expressed as:

$$\partial = \alpha l \Delta T \quad (4)$$

$$\varepsilon = \alpha \Delta T \quad (5)$$

According to Hooks law of deformation

$$\varepsilon = \sigma/E \quad (6)$$

Comparing equation (5) and equation (6)

$$\sigma/E = \alpha \Delta T$$

$$\Delta T = \sigma/\alpha E \quad (7)$$

The material index is $M2 = \sigma/\alpha E$

The performance matrices given in Table 2 were calculated based on various scales set for material's properties. Each property was assigned a particular value based on the application's requirements. The materials shown in table 2 were shortlisted after screening and ranking from materials universe. The combination of various properties such as high heat transfer, lower thermal expansion, thermal and chemical stability in an inert atmosphere, thermal conductivity and fabrication cost finalized the top three materials for MCHE shown in Table 3.

Table 2. Summary of material's performance for high-temperature MCHE applications

Material	High temperature performance T(K) and corrosion resistance	Thermal Conductivity K (W/m K)	Specific Heat C_p (J/Kg K)	Thermal Expansion α (μ.m/m. K)	Elastic Limit E (MPa)	Price (USD/kg)	Hardness H (MPa)	Density ρ (Mg/m^3)	Total Performance ∑R	Performance ratio ∑R/∑r
Silicon Carbide	Resist at <1300 ℃ (S)	10*9=90	7*10=70	3*5=15	8*7=56	5*7=35	4*7=28	2*7=14	308	7.89
Aluminum Nitride	Satisfied	10*10=100	7*10=70	3*9=27	8*5=40	5*7=35	4*2=8	2*9=18	298	7.64

Tungsten Carbide	Satisfied	10*5=50	7*5=35	3*10=30	8*7=56	5*5=25	4*2=8	2*2=4	208	5.33
Tungsten	Satisfied	10*10=100	7*2=14	3*7=21	8*5=40	5*5=25	4*5=20	2*2=4	224	5.74
Tungsten ASTM class 1 W 90%	Satisfied	10*7=70	7*2=14	3*7=21	8*9=72	5*5=25	4*10=40	2*9=18	260	6.76
Tungsten ASTM class 4 W97%	Satisfied	10*9=90	7*2=14	3*7=21	8*9=72	5*2=10	4*10=40	2*9=18	265	6.80
Elkonite 10 Cu Tungsten alloy	Satisfied	10*5=50	7*2=14	3*9=27	8*9=72	5*7=35	4*9=36	2*9=18	252	6.46
Alumina	Satisfied	10*2=20	7*10=70	3*10=30	8*7=56	5*9=45	4*2=8	2*9=18	247	6.33
Nickel Alloy	Satisfied	10*2=20	7*7=77	3*10=30	8*7=56	5*7=35	4*9=36	2*5=10	264	6.85
TZM alloy	Satisfied	10*9=90	7*5=35	3*9=27	8*9=72	5*7=35	4*9=36	2*9=18	313	7.02

Table 3. Materials properties of performance based selected materials.

S. No.	Material	Thermal conductivity (W/m.℃)	Heat Capacity (J/kg. ℃)	Thermal expansion coefficient (10^{-6} /K)	Density (kg/m^3)
2	Silicon Carbide	80-130	663-800	4-4.8	3210
2	TZM (Mo 99.40%, Ti 0.5%, Zr 0.08%, and C 0.02%)	200	305	4.5	10241
3	Aluminum Nitride	140-200	780-820	4.9-5.5	3260

Conclusion

The micro channel heat exchanger’s compactness, reduction in weight and size along with heat transfer enhancement has showcased their promising and preferable choice in waste heat recovery and other applications. However, higher manufacturing cost and material’s degradation in the harsh environment has limited MCHE commercialized applications. CES software package identified some common materials for high-temperature MCHE applications. Thermal properties considered, included maximum service temperature, long term chemical stability, thermal conductivity, corrosion resistance, heat capacity, thermal expansion coefficient and cost of the materials. Suitable materials included metal alloys such as tungsten and nickel alloy, TZM alloy and ceramics such as alumina, aluminum nitride, silicon carbide, and tungsten carbide. Metal alloys such as aluminum are used commercially in low-temperature micro channel heat exchanger’s applications but are unsuitable for high-temperature above 500 ℃ applications. The economical assessment was made on the basis of the market price in (USD/kg). Silicon carbide and alumina were found to be the cheaper materials than tungsten carbide and aluminum nitride. The high-temperature ceramics such as silicon carbide, aluminum nitride and molybdenum alloy (TZM) were identified as promising materials for MCHE waste heat recovery. Their thermal and chemical stability for the extended period made them the best suited materials for high-temperature applications.

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