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Materials Design and Selection Issues in Ultra-Lean Porous Burners

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Abstract

The Laboratory for Sustainable Technology is developing a commercial porous burner for the ultra-lean combustion of gaseous fuels. Such a technology could be used to mitigate significant amounts of greenhouse gas emissions through the combustion of very low concentration, anthropogenic methane sources. Enhanced combustion is possible within porous burners because of the recirculation of energy between the porous medium and the fuel stream. The challenge of this research involves enhancing the heat recirculation, through an adroit combination of materials and structures, to enable combustion of ultra-lean mixtures. A laboratory-scale porous burner system has already been developed to enable fundamental studies on a range of procured materials. This paper provides an introduction to this research and includes preliminary results showing the burner performance. The improved understanding of materials design and performance that will result from this research will enable the lean limit of combustion to be extended in porous burners.

1 INTRODUCTION

An increased focus on fugitive emissions has been created by heightened environmental and economic concerns over global warming. Anthropogenic methane emissions are the second highest contributor to the greenhouse effect after carbon dioxide. Approximately 14% of worldwide[1] anthropogenic greenhouse gas emissions were due to methane in 2004. The high global warming potential of methane is an important factor in its contribution to worldwide greenhouse gas emissions. In fact, methane has 25 times[2] the global warming potential of carbon dioxide, due to its long life and indirect influences. One method of reducing the global warming impact of these fugitive emissions is to convert the methane to carbon dioxide via combustion, so as to generate an overall reduction[3] (approximately 89%) in global warming potential.

Coal mine ventilation air (MVA) accounts for a significant proportion of worldwide methane emissions (over 230 million tonnes of carbon dioxide equivalents in 2000[4]). The methane contained in MVA is normally released to the atmosphere, because stable and efficient mitigation is very difficult. These mitigation difficulties arise from the very low methane content and large gas volumes that are typical of MVA. Methane combustion is normally only possible within the limits of flammability, which are 5 volume percent (vol%) and 15 vol% methane for laminar flames in air[5]. The corresponding equivalence ratios (the fuel to air ratio compared to the stoichiometric fuel to air ratio) are 0.50 and 1.7. In contrast, the methane concentration in mine ventilation air is generally less than 1 vol%[6], which corresponds to an equivalence ratio of 0.10. MVA is therefore classified as an ultra-lean fuel mixture, as it is far below the lower flammability limit. However, mine ventilation air can be readily captured and is therefore a methane source that has the potential to be mitigated by combustion. Therefore, new combustion techniques for mitigating greenhouse gases from very low concentration methane emissions, such as MVA, are highly desirable.

Porous burners are an exciting development in combustion engineering and have valuable attributes that may make them an important part of the solution. These systems no longer rely on traditional free flames, but actually contain the combustion reaction within the pores of a solid matrix (refer to Figure 1). This innovation produces improved efficiencies, reduced pollutant emissions, an enlarged stable operating power range and the ability to operate at lean concentrations[7-9]. The properties of the porous materials are of crucial importance to the combustion performance. Therefore, our challenge is to enhance the porous burner materials design, so as to enable combustion of ultra-lean fuel mixtures.

Figure 1 The heated surface of a volumetric porous burner.

A brief overview of porous burner technology and a summary of the currently used materials are presented in this paper. Extensive research is required to provide a fundamental basis for an advanced materials design. Through this research the Laboratory for Sustainable Technology will create an optimised materials design for an ultra-lean porous burner system, which should result in significant environmental benefits.

2 POROUS BURNER TECHNOLOGY

The significant benefits of porous burner technology have been recognised in a number of technology reviews[8, 10-15] and recently Wood & Harris[16] highlighted the potential of porous burners for lean combustion applications. An example of a volumetric porous burner is given in Figure 1. Energy transfer within the burner causes some heat of reaction to preheat the fuel mixture prior to combustion[11]. This heat recirculation process alters the conditions within the porous burner and leads to enhanced combustion behaviour.

The recirculation of energy from the combustion reaction may include contributions from multiple thermal transport pathways. The dominant heat transfer mechanisms have been identified as:[17-19]

- solid-solid radiation,
- solid conduction within the porous medium, and
- thermal convection from the hot solid matrix to the incoming fuel mixture in the upstream section of the burner.

The heat transfer mechanisms within an idealised tube are shown in Figure 2. An analogous situation occurs within the pore structure in a porous burner, with the added complexity of multiple solid surfaces and altered gas flow paths. Therefore, the heat transfer characteristics of the porous solid are crucial to the heat recirculation within a porous burner.

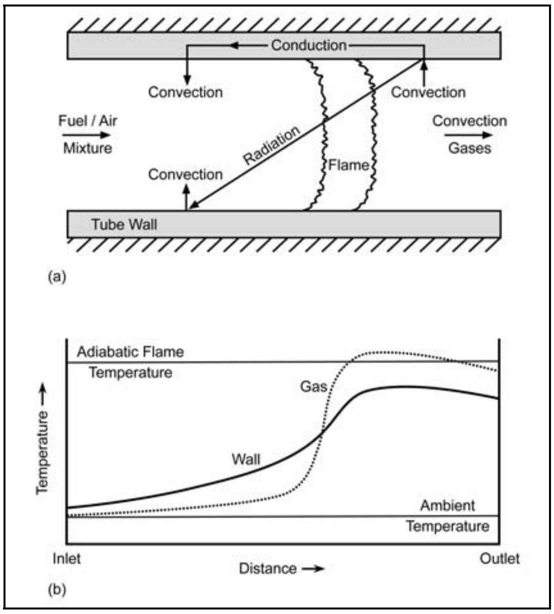

Figure 2 a) Schematic of heat transfer within a tube and b) the corresponding temperature profile (based on [13])

2.1 Stable Operation

A controlled flame front is required in a volumetric porous burner to maintain the desired combustion behaviour for safe and efficient operation over a wide range[20]. Flame stabilisation within a porous burner can be considered to be a direct consequence of the energy balance within the system. That is, a stabilised combustion reaction is created by the balance between the energy loss (or output) from the system, the chemical reaction energy input and the internal heat recirculation[21]. A number of energy-balanced regimes are possible in a volumetric porous burner, which allows a range of 'safe' operating conditions without unstable flame propagation. A stability envelope can be plotted to characterise the burner performance over a range of firing rates (or flow rates) and fuel mixtures, as shown in Figure 3.

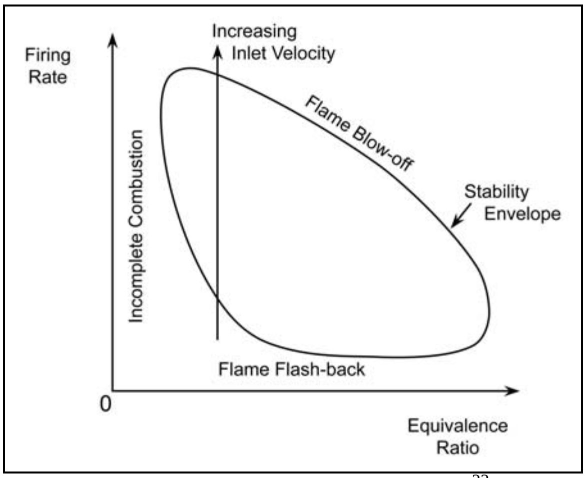

Figure 3 Burner stability envelope (based on [22])

The lean limit (low equivalence ratio) of stable burner operation is generally caused by incomplete combustion at low firing rates or flame blow off at high firing rates. Blow off occurs when the combustion zone propagates downstream and exits the burner end (or leaves the burner surface)[12, 20, 23, 24]. The material properties have been shown to be crucial to the onset of these instabilities[25]. Therefore, materials selection is important to the range of stable operation in porous burners.

2.2 Lean Combustion Performance

Research into ultra-lean combustion in porous burners has not been extensive, despite the technology's suitability for combusting lean fuel mixtures[7, 8, 11]. Mößbauer[7] states that the operating range commonly used for porous burners is 0.53 – 0.91 equivalence ratio for methane/air mixtures. Few researchers have combusted mixtures that are leaner than this range, particularly near the 0.10 equivalence ratio typical of MVA. However, some recent studies have examined the combustion of low calorific value and ultra-lean mixtures in porous burners.

Al-Hamamre and colleagues[26] proposed that landfill gas and waste pyrolysis gas could be burnt in a porous medium burner. These waste gases typically have high inert gas content and therefore low heating values (<7 MJ/m^3 is typical[27]). The presence of inert gases in a fuel/oxidiser mixture acts to reduce the combustion temperature, as the inactive species absorbs some of the energy from the reaction leading to a narrower range of stable operation[26, 27]. Al-Hamamre and colleagues identified that the degree of gas preheating prior to entry and within the burner was critical to the successful combustion of low calorific value gases. This research has shown that porous burner technology has the potential to be used for the combustion of low calorific gases, but further work is required for low equivalence ratio fuels.

Afsharvahid, Christo and others[28-31] considered porous burner technology as a mechanism of ultra-lean mixture combustion. A porous burner design was proposed and preliminary experimental and numerical work was performed. The porous burner was comprised of flint clay in the upstream layer and alumina beads in the downstream layer. In a technical report on the project[31] ultra-lean mixtures (equivalence ratio of 0.2 and 0.1) were reported as being stably combusted at a low firing rate. However, the validity of these results must be questioned, as the stable operating time was not provided and the influence of residual heat from the combustion of richer fuel mixtures was not considered. Published research[28] reported stable combustion of lean mixtures (equivalence ratio of 0.35 and 0.4) in the burner. However, no further published work is available from these authors on this project and it must be concluded that stable combustion of ultra-lean mixtures was not consistently achieved. Therefore, porous burners have recognised potential for ultra-lean methane combustion, but further research is required to establish viability.

2.3 Summary

Porous burners are well established as a useful and versatile technique for lean combustion. The porous media's properties are crucial to the extent of heat recirculation within a burner. Past research has shown that further design optimisation is required if ultra-lean gas mixtures are to be stably combusted.

3 MATERIALS DESIGN

Materials selection is the most important design consideration for porous burners as it determines the combustion performance, the longevity and the system's versatility. The materials used in porous burners are based upon a combination of base material type and porous structure.

3.1 Current Materials

Ceramic materials are more widely used than metals in porous burners due to their comparative elevated temperature stability[32]. Alumina (Al_2O_3), zirconia (ZrO_2) and silicon carbide (SiC) based materials are the most commonly used materials in porous burners. Other ceramics and high-temperature metals have only been occasionally employed.

3.1.1 Alumina

Alumina is often selected as a porous burner material as it is a durable, high temperature, hard and chemically stable material that is relatively inexpensive[33]. However, its use is limited by a relatively low thermal conductivity and poor resistance to thermal shock[32]. Alumina has been employed in a variety of configurations in porous burners. Discrete alumina media[30, 31, 34-39], continuous alumina mixer structures[40-43] and cellular foams[44] have all been used as the primary burner material. However, alumina and alumina based ceramic matrix composites are recognised as a more appropriate material for the preheat section in a porous burner, because of limited thermal conductivity and radiative transport properties[45]. Multi-channel plates or monoliths are common structures used in this situation[26, 45-48]. In summary, alumina is a common porous burner material, but its use has been restricted to certain zones by limited thermal transport properties.

3.1.2 Zirconia

Zirconia-based materials have excellent high temperature resistance, but very low thermal conductivity and poor thermal shock resistance[32]. Yttria stabilised tetragonal zirconia polycrystal structure (TZP)[49-52], yttria- stabilised zirconia-alumina composite[17, 20, 53] and magnesia partially-stabilised zirconia (PSZ)[49, 52] are the main types used in porous burner systems. Other studies using partially-stabilised zirconia[25, 54, 55] did not specify the type of dopant. Zirconia cellular foam is commonly used as both the primary burner material[17, 20, 25, 49, 53, 54, 56, 57] and the preheating material only[41]. Zirconia foam has also been manufactured into a three-dimensional mixer structure by pre-machining into a lamellae shape prior to ceramic slurry infiltration[58]. However, the poor heat transport and thermal shock resistance have limited the use of zirconia media in recent porous burner applications.

3.1.3 Silicon-Carbide

Silicon carbide is a desirable material in the combustion region of porous burners, due to excellent heat transport properties and good thermal shock performance[10]. However, the corrosion performance of silicon carbide under extreme conditions can be restricted, as it is reliant upon the formation and resilience of a protective silica scale[59]. Silicon carbide foam has been used extensively in the combustion zone[40, 43, 45-49, 60-62] of porous burners. Silicon carbide coated, carbon foams have also been used successfully in multi-layer burners[63-65]. Silicon carbide lamellae structures are another useful material for the combustion zone of a two-stage burner[41, 58, 66, 67].

Other types of silicon carbide structures, such as ceramic fibre mats[68] and particles[38] have been used less frequently. In summary, the good thermal transport properties of silicon carbide make it suitable for the combustion zone in porous burners.

3.1.4 Other Ceramics

Only a few examples exist of other ceramic materials in porous burners. In work conducted by Mathis and Ellzey[20], a mullite (zirconia-toughened) foam burner was prone to flashback because of its material properties. In other research[69], the relative low temperature resistance of lithium aluminium silicate foam restricted a porous burner to lean equivalence ratio combustion only. A silicon carbide coated, cordierite foam material was used by Mital and colleagues[24], but unfortunately no durability or material performance information was given. Finally, flint clay has also been used in the preheat zone of two-stage burners designed for lean[30, 31, 39] and rich[60] methane combustion.

3.1.5 Metals

Metallic materials are not commonly used in volumetric porous burner applications because of their limited high temperature performance. However, nickel-based superalloys, iron-chromium-aluminium alloys (FeCrAlloys) and to a lesser extent stainless steel have all been considered or used in past porous burner research.

Nickel-based superalloys have been designed to operate at high-temperatures whilst maintaining resistance to creep, fatigue and environmental degradation[70, 71] and a variety of alloys exist with tailored properties[72]. However, the incipient melting temperature of nickel-based superalloys is generally lower than approximately 1330°C[71], which limits their use at very high temperatures without a protective coating. Nickel superalloys have not used in any published volumetric porous burner applications, but a NiCrAl alloy was used in a surface radiant burner[73].

FeCrAl alloys are considered to be a suitable metallic material for high temperature applications, because of the oxidation resistance generated by the growth of a protective alumina scale[74]. FeCrAlloys have good thermal shock resistance and are temperature resistant to approximately 1200°C[75, 76]. FeCrAlloy has been used as the material for radiant surface porous burners[77, 78], catalytic surface burners[79, 80] and as the material for a volumetric porous burner[23].

Austenitic stainless steel alloys retain good mechanical properties and corrosion performance at moderate temperatures[81]. In one rare example, stainless steel wire bundles of an undisclosed alloy type were used in a volumetric porous burner by Huang and colleagues[82]. Temperatures typically below 1000°C were recorded during these experiments. The long-term material durability was not disclosed and must be of concern.

In summary, the upper service temperature of metallic materials has been a limitation to their widespread use. However, these metallic materials could be considered for burners with lower peak temperatures or for regions consistently experiencing lower temperatures.

3.2 Current Structures

3.2.1 Discrete Elements

Porous beds of discrete elements have been used in a number of porous burner investigations. Ceramic balls[34], ceramic pebbles[36-38] and ceramic saddles[83] (refer to Figure 1) are the main discrete element media used in published porous burner research. Discrete media designed for catalytic applications could be used in porous burners to provide a vast range of multi-modal pore sizes, porosities and shapes. One type is shown in Figure 4.

Figure 4 Dytech Turbocat alumina packing material[84]

Porous burner designs have predominantly been based on foam and mixer structures rather than beds of discrete elements[7]. The relatively high pressure drop across the bed of individual media is the primary reason for their restricted use[10, 32]. Another minor disadvantage is the requirement for a retaining structure to prevent the loss of the individual media[11]. However, laboratory studies have shown that this would only occur at very high flow rates. The main stated advantage[11, 34] of discrete elements is the improved durability compared to a rigid and continuous structure. In addition, the solid discrete elements would also provide significant heat capacity to the porous burner system. This thermal inertia may be an advantage for stability under variable combustion conditions, but a disadvantage for quick start-up times.

3.2.2 Cellular Structures

Cellular structures are the most commonly used materials in porous burners. These structures are defined as an array of hollow cells where the porosity is normally larger than 70%[85]. An image of a ceramic foam is shown in Figure 5.

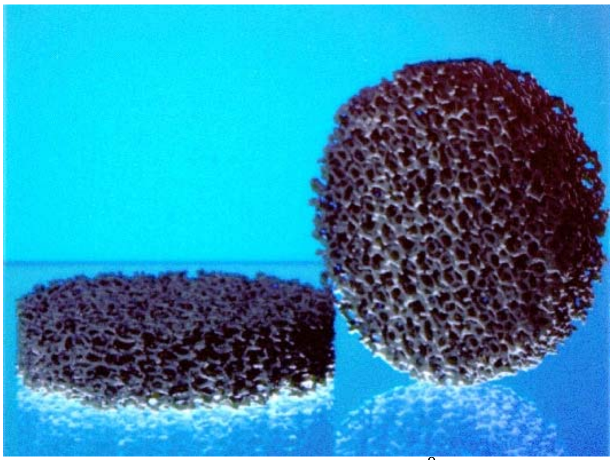

Figure 5 Silicon carbide open-cell foam[9]

As seen in the image above, foams are comprised of fine interconnecting struts. The foams are available in a wide range of porosities and pore sizes. Improved gas mixing, reduced weight and low pressure loss are some of the reasons why foams are selected for porous burners[32, 58]. However, the durability of the rigid structure has been one important restriction. Ceramic foams are generally used due to their high temperature performance, although a range of metal foam materials and structures are commercially available[86-88] and have occasionally been developed for porous burner purposes[78].

3.2.3 Mixer Structures

Complex mixer structures are also frequently employed in porous burner research[26, 40-42, 58, 67]. This media is characterised by three dimensional interwoven lamellae, as shown in Figure 6.

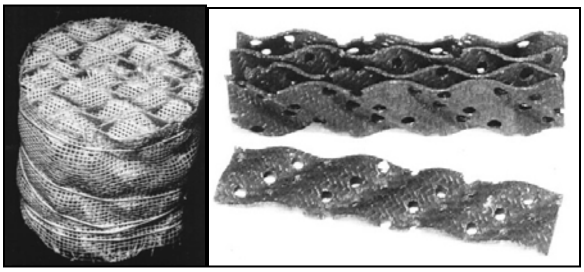

Figure 6 Woven alumina mixer structure and punched silicon carbide lamallae[41]

The lamellae can be made of punched, woven fibre, solid or foam. Both ceramic and metal structures have been made. Pickenacker, Trimis and colleagues[7, 32, 58] have highlighted the benefits of these structures for porous burner applications. In general, these structures have high porosity and therefore relatively small heat capacity. The relatively high surface area also leads to relatively high radiative heat transport. The structures also have limited, but anisotropic thermal conductivity.

3.2.4 Other Structures

Monolithic structures are suited for the preheat zone of a porous burner, as they generally have low thermal conductivity and limited radiative heat transfer, which helps reduce the possibility of flame flashback. Indeed, an alumina composite monolith with multiple pore channels was chosen as the preferred porous structure in the preheat zone of a porous burner in recent research[45]. Monoliths are not favoured for use in the combustion region in a volumetric porous burner, as other interconnected and tortuous porous structures provide extensive gas mixing. Monoliths in contrast provide separate and uniform gas flow[76].

Fibrous structures have been suggested as another material for use in volumetric porous burners[7, 82]. Fibrous structures are likely to suffer from quick degradation, due to the thin components. The low material density also limits the heat capacity and the thermal conductivity, but the relative high surface area of the structure should correspond to a higher level of radiative transfer[7]. Fibrous structures have not been widely used in volumetric porous burner technology.

3.3 Summary

The dominant porous burner materials are structural ceramics, whilst common structures include beds of discrete elements, cellular foams and mixer structures. Alumina packed bed or monoliths are commonly favoured for the pre-heat zone of a volumetric porous burner due to their low conductivity and low optical depth. The combustion zone, in contrast, requires materials that facilitate a high degree of heat transport and silicon carbide is a popular material choice due to its high thermal conductivity. Cellular and mixer structures are commonly used in the combustion zone as the materials allow significant gas mixing.

4 EXPERIMENTAL ANALYSIS TECHNIQUES

4.1 Introduction

Fundamental experimental examination of materials design of a range of porous materials will be conducted in a laboratory system. Combustion behaviour will be monitored by temperature profile and exhaust gas analysis over a range of firing rates and equivalence ratios. A set of stability envelopes will be established through this work, which clearly indicates the lean operating performance of the materials design considered. A range of typical porous materials will be examined. Analysis of the influence of material properties on burner behaviour will then be possible based on these experimental results.

Numerical analysis of the laboratory scale porous burner will supplement the experimental analysis. A computational fluid dynamics software package provides the basis for this research. The model also includes heat transfer mechanisms to allow comprehensive analysis. However, a detailed discussion of the numerical analysis is outside the scope of this paper.

4.2 Experimental Design

A basic laboratory scale porous burner system was designed and built by the Laboratory for Sustainable Technology. The combustion chamber was based upon designs found in the literature, especially those by Ellzey and colleagues at the University of Texas, Austin (see [53] for example). The burner chamber is shown in Figure 7.

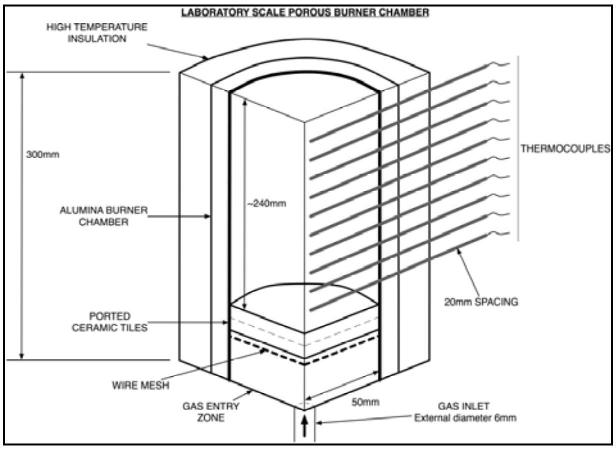

Figure 7 Schematic of the porous burner chamber, with no porous media shown for clarity

The entry to the alumina combustion chamber includes flow conditioning and ported ceramic tiles to prevent flame flash back into the gas inlet line. The burner chamber is approximately 240 millimetres in depth, but the porous bed depth can be adjusted over the length of the chamber. The diameter of the burner is 100 millimetres and the chamber is 20 millimetres thick. The chamber is wrapped in high temperature insulation to a depth of approximately 100 millimetres.

The porous burner system is comprised of the following components:

- Air supply, air drier and flow regulator (Alicat 0-200 standard litres per minute, mass flow controller),
- Fuel supply and flow regulator (Alicat 0-20 standard litres per minute, mass flow controller),
- Inline heat exchanger,
- Burner chamber,
- Thermocouples (3mm diameter Inconel 600 MIMS K-type and 1.5mm Pyrosil MIMS K-Type),
- Exhaust gas analysis system (ADC MGA-3000 Series Multi-Gas Analyser), and
- Data acquisition system.

The laboratory system is shown schematically as a piping and instrument diagram in Figure 8.

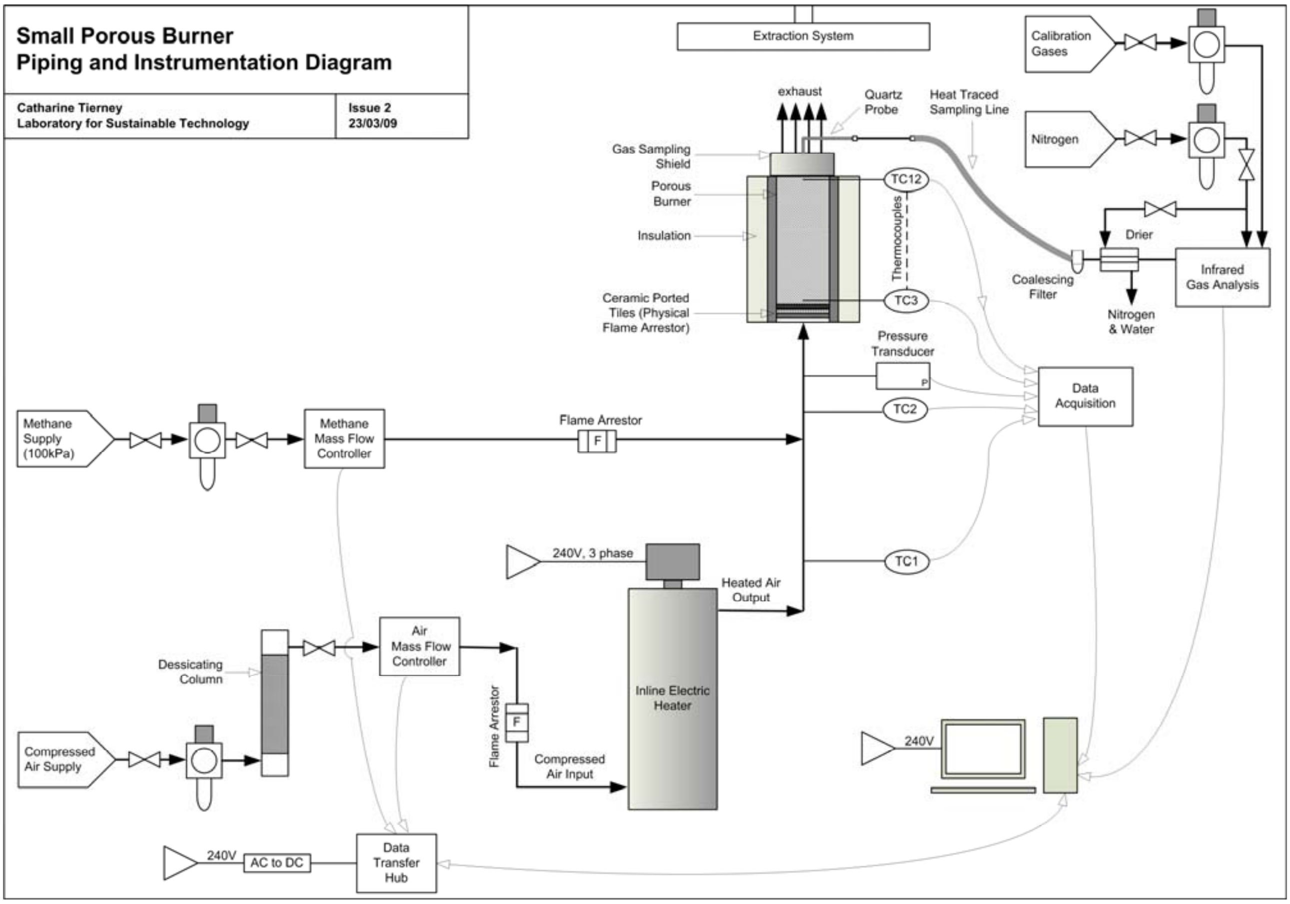

Figure 8 Piping and instrumentation diagram for the laboratory porous burner system

4.3 Materials for Analysis

Over thirty different porous materials have been procured for examination in the laboratory scale porous burner. A summary of the different types of materials obtained is given in Figure 9.

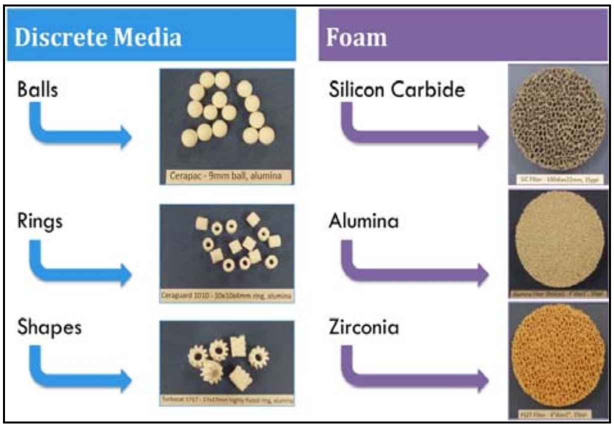

Figure 9 Summary of the porous materials available

Discrete media and ceramic foams were selected as the primary materials for examination. Thin ceramic foam pieces were obtained for improved robustness and versatility of design.

5 PRELIMINARY RESULTS

Work has commenced on establishing the base operating behaviour of the burner system to act as a benchmark for future burner operation. The base material combination selected has been used successfully in pilot-scale trials and is comprised of a preheat layer of flint clay (approximately 10 millimetres depth) and an alumino-silicate ceramic saddle combustion zone (approximately 230 millimetres depth). A stability envelope will be established for the burner design showing the performance over a range of combustion conditions. However, only a limited range of firing rates and equivalence ratios has been examined thus far.

A typical experimental output at a firing rate of 300 kW/m^2 is shown in Figure 10. The methane concentration is shown in the uppermost graph, over the operating time, and the corresponding temperature profiles is given in the lower graph in Figure 10. The temperature measurements are organised in order of burner height. That is, Thermocouple 3 was placed in the lowest thermocouple port in the burner chamber and Thermocouple 12 in the highest.

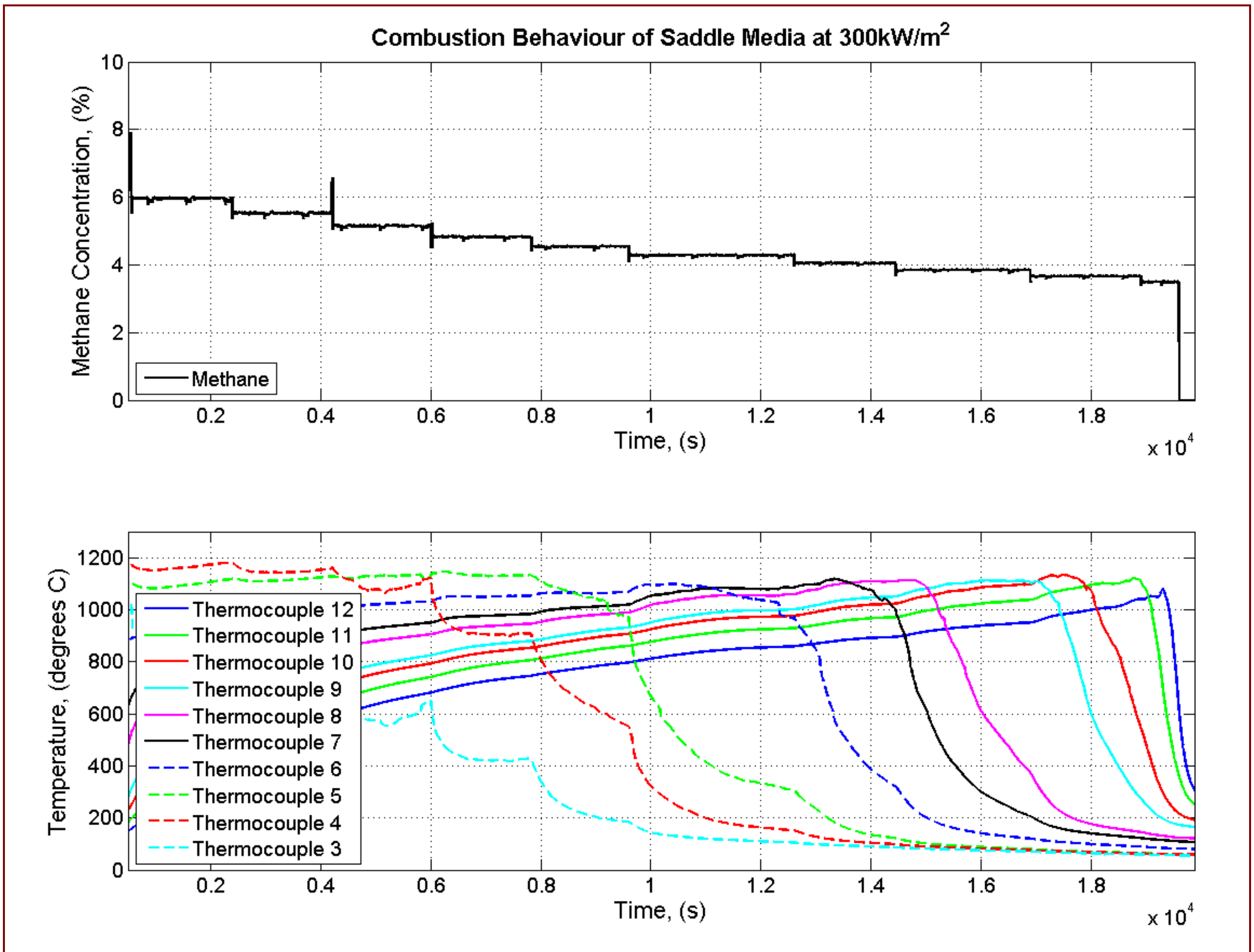

Figure 10 Typical experimental output for one media type at 300kW/m^2 firing rate, uppermost graph showing methane concentration over time and lower graph showing corresponding temperature profile

The concentration of fuel in the inlet gas mixture was decreased step-by-step in this experiment, by increasing the proportion of air in the mixture (and thereby maintain a constant firing rate of 300kW/m^2). The temperature profiles show a corresponding shift in the peak temperature downstream. This behaviour is in accordance with other porous burner systems. It is interesting to note that combustion was successful for this base case design at 3.8% methane concentration, before the onset of blow-off. This lean operation level is well below the normal lower flammability limit for methane of 5%. Therefore, there is significant potential for achieving ultra-lean combustion in porous burners with an advanced design.

6 CONCLUSIONS AND FUTURE RESEARCH

Porous burner systems have been identified as a new technique for ultra-lean methane emission mitigation. However, ultra-lean methane mixtures have yet to be successfully combusted in porous burners. Therefore, significant research is required to improve the understanding of burner design for ultra-lean combustion conditions. A laboratory burner system has been designed to address this deficiency. The preliminary phase is underway and comprehensive, fundamental experimental research will be conducted so as to provide a basis for the development of an advanced porous burner design for ultra-lean combustion.

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REFERENCES

1 IPCC *Climate Change 2007: Synthesis Report*, Intergovernmental Panel on Climate Change: 2007.
2 P. Forster, V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey, J. Haywood, J. Lean, D. C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, *Changes in Atmospheric Constituents and in Radiative Forcing*, In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, Eds. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2007.
3 ACARP *Mitigation of Methane in Mine Ventilation Air 2006 Status Report*, Australian Coal Association Research Program: April, 2007.
4 US EPA *Assessment of the Worldwide Market Potential for Oxidizing Coal Mine Ventilation Air Methane*, United States Environmental Protection Agency: July, 2003.
5 I. Glassman, *Combustion*. 3rd ed., Academic Press: San Diego, Calfornia, 1996.
6 US EPA *Technical and Economic Assessment: Mitigation of Methane Emissions from Coal Mine Ventilation Air*, EPA-430-R-001; US Enivronmental Protection Agency: 2000.
7 S. Mossbauer, O. Pickenacker, K. Pickenacker and D. Trimis, *Application of the Porous Burner Technology in Energy- and Heat- Engineering*, In Fifth International Conference on Technologies and Combustion for a Clean Environment (Clean Air V), Lisbon, Portugal, 1999, Vol. 1, pp 519-23.
8 D. Trimis and F. Durst, *Combustion Science and Technology* 1996, vol 121, (1), pp 153 - 68.
9 D. Trimis, F. Durst, O. Pickenacker and K. Pickenacker In Porous Medium Combustor versus Combustion System with Free Flames, *2nd International Symposium on Heat Transfer Enhancement and Energy Conservation*, Guangzhou, China, 1997; S.-P. Wang and Y.-K. Tan, Eds. South China University of Technology Press: Guangzhou, China, 1997, pp 339-45.
10 F. Durst and D. Trimis, *Clean Air* 2002, vol 3, (1), pp 1 - 20.
11 J. R. Howell, M. J. Hall and J. L. Ellzey, *Progress in Energy and Combustion Science* 1996, vol 22, (2), pp 121-45.
12 M. M. Kamal and A. A. Mohamad, *Proceedings of the Institution of Mechanical Engineers Part a-Journal of Power and Energy* 2006, vol 220, (A5), pp 487-508.
13 R. Viskanta and J. P. Gore, *Environ. Combust. Technol.* 2000, vol 1, pp 167-203.
14 A. A. M. Oliveira and M. Kaviany, *Progress in Energy and Combustion Science* 2001, vol 27, (5), pp 523-45.
15 M. A. Mujeebu, M. Z. Abdullah, M. Z. A. Bakar, A. A. Mohamad and M. K. Abdullah, *Progress in Energy and Combustion Science* 2009, vol 35, (2), pp 216-30.
16 S. Wood and A. T. Harris, *Progress in Energy and Combustion Science* 2008, vol 34, (5), pp 667-84.
17 A. J. Barra and J. L. Ellzey, *Combustion and Flame* 2004, vol 137, (1-2), pp 230-41.
18 S. B. Sathe, R. E. Peck and T. W. Tong, *International Journal of Heat and Mass Transfer* 1990, vol 33, (6), pp 1331-38.
19 Y. Yoshizawa, K. Sasaki and R. Echigo, *International Journal of Heat and Mass Transfer* 1988, vol 31, (2), pp 311-19.
20 W. M. Mathis and J. L. Ellzey, *Combustion Science and Technology* 2003, vol 175, (5), pp 825-39.
21 Y. Kotani and T. Takeno, *Symposium (International) on Combustion* 1982, vol 19, (1), pp 1503-09.
22 E. Garcia, P. Miranzo and M. I. Osendi, *Recent Res. Dev. Mater. Sci.* 2003, vol 4, (Pt. 2), pp 737-54.
23 B. J. Vogel and J. L. Ellzey, *Combustion Science and Technology* 2005, vol 177, (7), pp 1323-38.
24 R. Mital, J. P. Gore and R. Viskanta, *Combustion and Flame* 1997, vol 111, (3), pp 175-84.
25 A. J. Barra, G. Diepvens, J. L. Ellzey and M. R. Henneke, *Combustion and Flame* 2003, vol 134, (4), pp 369-79.
26 Z. Al-Hamamre, S. Diezinger, P. Talukdar, F. Von Issendorff and D. Trimis, *Process Safety and Environmental Protection* 2006, vol 84, (B4), pp

297-308.
27 J. Chomiak, J. P. Longwell and A. F. Sarofim, *Progress in Energy and Combustion Science* 1989, vol 15, (2), pp 109-29.
28 S. Afsharvahid, B. B. Dally and F. C. Christo, *On the stabilization of ultra-lean methane and propane flames in porous media*, In The Fourth Asia-Pacific Conference on Combustion, Nanjing, China, 2003, pp 56-59.
29 S. Afsharvahid, B. B. Dally and F. C. Christo, *Numerical Study of Flame Stabilisation Inside Porous Burner*, In 2003 Australian Symposium on Combustion & The Eighth Australian Flame Days, Monash University, Australia, 2003.
30 S. Afsharvahid, P. V. Lanspeary, B. B. Dally and F. C. Christo, *On the Design of an Ultra Lean Porous Burner*, In Australian Symposium on Combustion and The Seventh Australian Flame Days, Adelaide, Australia, 2002.
31 F. C. Christo, B. C. Dally, P. V. Lanspeary, S. Afsharvahid and S. D. Joseph, *Development of porous burner technology for ultra-lean combustion systems*, In South Australia Sustainable Energy Research Advisory Committee (SENRAC): Tech. Rep. GC-FR-F-220202, 2002.
32 O. Pickenacker, K. Pickenacker, K. Wawrzinek, D. Trimis, W. E. C. Pritzkow, C. Muller, P. Goedtke, U. Papenburg, J. Adler, G. Standke, H. Heymer, W. Tauscher and F. Jansen, *Interceram* 1999, vol 48, (5), pp 326-30.
33 G. L. DePoorter, T. K. Brog and M. J. Readey, *Structural Ceramics*, In ASM Handbook, ASM International Handbook Committee, Ed. ASM International: USA, 1990, Vol. 2 Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, pp 1019-24.
34 V. Bubnovich, L. Henriquez and N. Gnesdilov, *Numerical Heat Transfer Part A - Applications* 2007, vol 52, (3), pp 275-95.
35 F. Contarin, W. M. Barcellos, L. A. Kennedy and A. V. Saveliev, *Journal of Heat Transfer* 2005, vol 127, (2), pp 123(8).
36 L. A. Kennedy, A. A. Fridman and A. V. Saveliev, *Fluid Mechanics Research* 1995, vol 22, (2), pp 1-26.
37 L. A. Kennedy, A. V. Saveliev, J. P. Bingue and A. A. Fridman, *Proceedings of the Combustion Institute* 2002, vol 29, pp 835-41.
38 T.-Y. Xiong, M. J. Khinkis and F. F. Fish, *Fuel* 1995, vol 74, (11), pp 1641-47.
39 S. Wood, D. F. Fletcher, A. T. Harris, S. Joseph and A. Dawson, *International Journal of Environment and Waste Management* In Press, vol, pp.
40 Z. Al-Hamamre, S. Voss and D. Trimis, *Detailed experimental and numerical investigation of the partial oxidation of methane in a porous reactor*, In Proceedings of the European Combustion Meeting, 2007.
41 G. Brenner, K. Pickenacker, O. Pickenacker, D. Trimis, K. Wawrzinek and T. Weber, *Combustion and Flame* 2000, vol 123, (1-2), pp 201-13.
42 M. M. Kamal and A. A. Mohamad, *Journal of Porous Media* 2006, vol 9, (5), pp 469-81.
43 O. Pickenacker and D. Trimis, *Journal of Porous Media* 2001, vol 4, (3), pp 197-213.
44 X. Y. Zhou and J. C. F. Pereira, *Combustion Science and Technology* 1997, vol 130, (1-6), pp 335-64.
45 A. Mach, F. V. Issendorff, R. Krieger, J. Schafer, M. Schmucker, A. Herzog, B. Kanka, W. E. C. Pritzkow, J. Schmidt and H. Schneider, *Refractories Manual* 2006, vol, pp 48-55.
46 T. C. Hayashi, I. Malico and J. C. F. Pereira, *Clean Air (Redding, CT, U. S.)* 2007, vol 8, (2), pp 125-43.
47 T. Brehmer, F. Heger, K. Lucka, J. von Schloss, Y. Abu-Shareck, D. Trimis, A. Heeb, G. Kob, T. C. Hayashi, J. C. F. Pereira, M. Founti, D. Kolaitis, M. Molinari, A. Ortona, J.-B. Michel and P. Theurilliat, *BIOFLAM Project: Application of liquid biofuels in new heating technologies for domestic appliances based on cool flame vaporization and porous medium combustion*, In 7th International Conference on Energy for a Clean Environment, Lisbon, 2003, pp 11.3.
48 M. Steven, A. Mach, F. von Issendorff, M. Altendorfner and A. Delgado In Numerical simulation of combustion of a low calorific gas mixture in a porous inert medium taking anisotropic dispersion into account, *Third European Combustion Meeting (ECM2007)*, Chania, Greece, April, 2007; Chania, Greece, 2007.
49 M. Kaplan and M. J. Hall, *Experimental Thermal and Fluid Science* 1995, vol 11, (1), pp 13-20.
50 R. S. Dhamrat and J. L. Ellzey, *Combustion and Flame* 2006, vol 144, (4), pp 698-709.
51 M. Fay, R. Dhamrat and J. L. Ellzey, *Combustion Science and Technology* 2005, vol 177, (11), pp 2171-89.
52 M. K. El-Hossaini, M. Maerefat and K. Mazaheri, *Journal of Heat Transfer* 2008, vol 130, (3), pp 032601/1-01/5.
53 M. T. Smucker and J. L. Ellzey, *Combustion Science and Technology* 2004, vol 176, (8), pp 1171 - 89.
54 V. Khanna, R. Goel and J. L. Ellzey, *Combustion Science and Technology* 1994, vol 99, (1), pp 133-42.
55 P.-F. Hsu, W. D. Evans and J. R. Howell, *Combustion Science and Technology* 1993, vol 90, (1), pp 149 - 72.
56 C.-J. Tseng and H.-Y. Tsai, *Heat Transfer - Asian Research* 2006, vol 35, (1), pp 75-88.
57 N. Delalic, D. Mulahasanovic and E. N. Ganic, *Experimental Thermal and Fluid Science* 2004, vol 28, (2-3), pp 185-92.
58 O. Pickenacker, K. Pickenacker, K. Wawrzinek, D. Trimis, W. E. C. Pritzkow, C. Muller, P. Goedtke, U. Papenburg, J. Adler, G. Standke, H. Heymer, W. Tauscher and F. Jansen, *Interceram* 1999, vol 48, (6), pp 424-34.
59 N. S. Jacobson, *Journal of the American Ceramic Society* 1993, vol 76, (1), pp 3-28.
60 S. Afsharvahid, P. J. Ashman and B. B. Dally, *Combustion and Flame* 2008, vol 152, pp 604-15.
61 M. Altendorfner, F. Von Issendorff and M. Dannehl, *Development of a high pressure burner for industrial*

applications using porous inert media In 9th Conference on Energy for a Clean Environment (CleanAir IX), Portugal, 2007.
62 I. Malico, X. Y. Zhou and J. C. F. Pereira, *Combustion Science and Technology* 2000, vol 152, (1), pp 57 - 79.
63 T. L. Marbach and A. K. Agrawal, *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme* 2005, vol 127, (2), pp 307-13.
64 S. Vijaykant and A. K. Agrawal, *Experimental Thermal and Fluid Science* 2007, vol 32, (1), pp 117-25.
65 S. K. Alavandi and A. K. Agrawal, *International Journal of Hydrogen Energy* 2008, vol 33, (4), pp 1407-15.
66 J. Schmidt, M. Scheffler, A. Mach and F. V. Issendorff, *Highly Porous Non-Oxide Ceramic Matrix Composites (C/SiSiC and SiSiC) for Porous Burner Applications*, In Porous Ceramic Materials Conference, Brugge, 2005.
67 J. Schmidt, M. Scheiffele, A. Mach and F. von Issendorff, *Industrial Ceramics* 2007, vol 27, (2), pp 127-30.
68 D. Trimis, *Ceramic structures as supports for natural gas combustion*, In CIMTEC 2002 - 10th International Ceramics Congress and 3rd Forum on New Materials, P. Vincenzini, Ed. Techna Srl: 2003, Vol. 33, pp 311-22.
69 S. B. Sathe, M. R. Kulkarni, R. E. Peck and T. W. Tong, *Twenty-Third Symposium (International) on Combustion* 1990, vol, pp 1011-18.
70 W. L. Mankins and S. Lamb, *Nickel and Nickel Alloys*, In ASM Handbook, ASM International Handbook Committee, Ed. ASM International: USA, 1990, Vol. 2 Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, pp 428-45.
71 R. C. Reed, *The Superalloys: Fundamentals and Applications*. Cambridge University Press: Cambridge, 2006.
72 Stoloff, *Wrought and P/M Superalloys*, In ASM Handbook, ASM International Handbook Committee, Ed. ASM International: USA, 1990, Vol. Volume 1 Properties and Selection: Irons, Steels and High-Performance Alloys, pp 950-77.
73 S. Gauthier, E. Lebas and D. Baillis, *International Journal of Chemical Reactor Engineering* 2007, vol 5, pp.
74 J. Jedlinski, *Solid State Ionics* 1997, vol 101-103, (Part 2), pp 1033-40.
75 P. Avila, M. Montes and E. E. Miro, *Chemical Engineering Journal* 2005, vol 109, (1-3), pp 11-36.
76 R. E. Hayes and S. T. Kolaczkowski, *Introduction to Catalytic Combustion*. Gordon and Breach Scientific Publishers: Amsterdam, 1997.
77 S. A. Leonardi, R. Viskanta and J. P. Gore, *Journal of Heat Transfer* 2003, vol 125, (1), pp 118-25.
78 E. J. Cookson and D. E. Floyd, *High Temperature Materials and Processes* 2007, vol 26, (4), pp 269-74.
79 I. Cerri, M. Pavese, G. Saracco and V. Specchia, *Catalysis Today* 2003, vol 83, (1-4), pp 19-31.
80 D. Ugues, S. Specchia and G. Saracco, *Industrial and Engineering Chemistry Research* 2004, vol 43, (9), pp 1990-98.
81 *Elevated-Temperature Properties of Stainless Steels* In ASM Handbook, ASM International Handbook Committee, Ed. ASM International: USA, 1990, Vol. 1 Properties and Selection: Irons, Steels and High-Performance Alloys, pp 930-49.
82 Y. Huang, C. Y. H. Chao and P. Cheng, *International Journal of Heat and Mass Transfer* 2002, vol 45, (21), pp 4315-24.
83 S. Wood, D. F. Fletcher, S. Joseph, A. Dawson and A. T. Harris, *Design of a Porous Burner for the Oxidation of Methane in Mine Ventilation Air*, In CHEMECA 2006, B. R. Young, D. A. Patterson and X. D. Chen, Eds. Auckland, New Zealand, 2006.
84 Dytech *Catalyst Carriers*, http://www.dytech.co.uk/main.php?id=1&category=CATALYST%20CARRIERS (14/04/09),
85 D. J. Green and P. Colombo, *Cellular Ceramics: Intriguing Structures, Novel Properties, and Innovative Applications*, In MRS Bulletin, Materials Research Society: Warrendale, USA, 2003, Vol. 28, pp 296-300.
86 *Porvair Advanced Materials*, http://www.porvairadvancedmaterials.com/ (27/06/08),
87 Metafoam Technologies Inc. *Metafoam Technologies: Do it with metal foam*, http://www.metafoam.com/ (27/06/08),
88 H.-P. Degischer, *Handbook of Cellular Metals: Production, Processing, Applications*, Wiley-VCH Verlag: 2002, pp Pages.