Chapter

Impact of Porous Media on Combustion Processes and Waste Heat Recovery

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Abstract

Due to the demand for energy efficiency and sustainability, porous media has emerged as a promising solution due to its high surface area, structural versatility, and enhanced heat transfer performance. The application of porous media in combustion and waste heat recovery offers a wide range of fields for developing new efficient thermal technologies. Typically, these processes operate under turbulent regimes, where flow instabilities significantly influence chemical reactions and thermal transport; therefore, modeling turbulence is essential to capture the physical phenomena governing combustion behavior, flame stability, and heat exchange efficiency. Approaches based on Reynolds-Averaged Navier–Stokes equations and the Local thermal non-equilibrium model allow the description of the phenomenology governing porous media. This chapter provides a concise overview of the fundamentals of turbulent transport phenomena in porous media and highlights their role in advanced thermal systems. In addition, it reviews the current status of porous media combustion and waste heat recovery technologies, identifying their applications, challenges, and future trends.

Keywords: porous media, turbulence model, heat transfer, porous media combustion, waste heat recovery, thermoelectric generation

1. Introduction

The energy demand grows yearly, and fossil fuels predominate in total energy consumption. However, the excessive use of these fuels promotes severe energetic crises and environmental troubles such as global warming and acid rain, among others [1]. This overview has generated a significant boost within the scientific community in finding new energetic technologies to reduce the use of fossil fuels.

Some measures that can increase the energy efficiency of processes can include proper planning of the productive process, investment in energy-efficient equipment, recycling of energy in the industrial production process, and recovery of excess energy and subsequent utilization in other processes [2]. This search for more efficient and sustainable energy technologies has allowed the development of advanced thermal systems capable of producing cleaner energy and reusing the heat that is typically wasted. In this context, porous media (PM) have emerged as a promising solution, offering enhanced heat transfer capabilities and enabling both energy conversion and recovery in a compact and effective manner [3]. Including PM as metals foams, ceramics, or polymers in combustion systems or waste heat recovery (WHR) devices improves heat transfer due to the higher surface area and interconnected pores [4].

The porous media combustion (PMC) consists of the propagation of a reaction zone inside a PM. This approach offers several advantages compared with conventional systems, such as better heat distribution, more flame stability, and lower emission of pollutants [5]. The high thermal conductivity of the solids favors a thermally efficient thermal feedback mechanism, preheating the reactive mixture and increasing the overall efficiency of the process [6]. On the other hand, WHR refers to the heat typically wasted in exhaust flows, combustion gases, or heat surfaces, transforming it into valuable energy or electricity through technologies such as thermoelectric generators (TEGs) [7]. The PM offers a structure that can be designed to optimize heat transfer by conduction and convection [8].

In several thermal applications, the PMC and WHR occur in turbulent conditions. This is because the systems usually operate at high Reynolds numbers, generating chaotic flows. Turbulence plays a fundamental role in directly affecting the momentum, energy, and mass transport, accelerating the mixture among the reactive and increasing the heat transfer coefficients [9]. The combination of PMC and WHR enables the development of integrated energy systems that are more thermally efficient, consume less fuel, and significantly reduce emissions.

2. Theoretical principles

Porous materials are found vastly in nature. With the exception of metals, some dense rocks, and some plastics, virtually all solid and semisolid materials are porous to varying degrees [10]. Characterizing the porous structure are the average pore size d and porosity ϕ, which can be found in a wide range of values. These pores are usually filled with one or more fluids and could be interconnected, allowing the flow of fluids through the material [11]. With such frequent occurrence, the phenomena of flow in PM take place in many scientific and engineering applications. Some examples from various areas are as follows: fluidized bed combustion, enhanced oil reservoir recovery, underground spreading of chemical waste, chemical catalytic reactors, absorption/desorption columns, mass transfer through membranes, packed bed chromatography, salt water intrusion into coastal aquifers, transpiration cooling, dehumidifying, and enhanced combustion within porous matrix [12, 13]. In general, the transport in porous media can easily fall in the turbulent regime [14] and can be characterized by the presence of eddies and associated with a pore Re_d greater than 120 [15]. Motivated by the above, the research community has made efforts to study the transport characteristics in PM [14, 16–21].

To numerically simulate the turbulent flow, it is necessary to calculate the motion of all eddies. However, the difference in scale between eddies increases as Reynolds numbers increase, becoming too computationally expensive at high Reynolds numbers. In this sense, adopting some approaches to solve the Navier–Stokes equations in PM is necessary.

2.1 The double decomposition

Derivation of mathematical macroscopic models of turbulence in PM requires a double decomposition (time and space) for every property ξ within the porous system and subsequent corresponding average operations over local conservation equations [13]. Following Pedras et al. [22], the intrinsic $\langle\cdot\rangle^{\mathrm{i}}$ and volumetric $\langle\cdot\rangle$ averages are related through the porosity ϕ:

$$\langle\xi\rangle^{\mathrm{i}} = \frac{1}{\Delta V_i} \int_{\Delta V_i} \xi dV \tag{1}$$

$$\langle\xi\rangle = \phi\langle\xi\rangle^{\mathrm{i}} \tag{2}$$

$$\phi = \frac{\Delta V_i}{\Delta V} \tag{3}$$

The property ξ can then be defined as the sum of $\langle\xi\rangle^{\mathrm{i}}$ and a spatial deviation ${}^{\mathrm{i}}\xi$ within the Representative Elementary Volume (REV) for which by definition:

$$\left\langle {}^{\mathrm{i}}\xi \right\rangle^{\mathrm{i}} = 0 \tag{4}$$

$$\xi = \langle\xi\rangle^{\mathrm{i}} + {}^{\mathrm{i}}\xi \tag{5}$$

Statistical analysis is required in the classical (clear fluid) treatment of turbulent flow. For that, the time average operator $\bar{\cdot}$ allows to obtain the time averaged value of property ξ:

$$\overline{\xi} = \frac{1}{\Delta t} \int_t^{t+\Delta t} \xi dt \tag{6}$$

Figure 1 shows a representative elementary volume (REV) where the instantaneous property ξ can be defined as the sum of $\overline{\xi}$ and a time-fluctuating component ξ' for which by definition:

$$\overline{\xi'} = 0 \tag{7}$$

$$\xi = \overline{\xi} + \xi' \tag{8}$$

For a rigid medium, the volume of fluid (phase) ΔV_i will be dependent only on space and not on time [23]. If the time interval chosen for temporal averaging in 6 is the same for all REVs, then the volumetric average 1 commutes with the time average because both integrations domains are independent of each other [22]. Necessary to the development of macroscopic models are the relationships between volumetric average of derivatives and the derivatives of volumetric averages, which can be found in the literature as the Theorems of Local Volumetric Averaging [13, 23].

$$\langle\nabla\xi\rangle = \nabla\left(\phi\langle\xi\rangle^{\mathrm{i}}\right) + \frac{1}{\Delta V}\int_{A_i} \mathbf{n}_i \xi dS, \tag{9}$$

$$\langle\nabla\cdot\boldsymbol{\xi}\rangle = \nabla\cdot\left(\phi\langle\xi\rangle^{\mathrm{i}}\right) + \frac{1}{\Delta V}\int_{A_i} \mathbf{n}_i\cdot\boldsymbol{\xi} dS, \tag{10}$$

$$\left\langle\frac{\partial\xi}{\partial t}\right\rangle = \frac{\partial}{\partial t}\left(\phi\langle\xi\rangle^{\mathrm{i}}\right) - \frac{1}{\Delta V}\int_{A_i} \mathbf{n}_i\cdot(\mathbf{u}_{A_i}\xi) dS \tag{11}$$

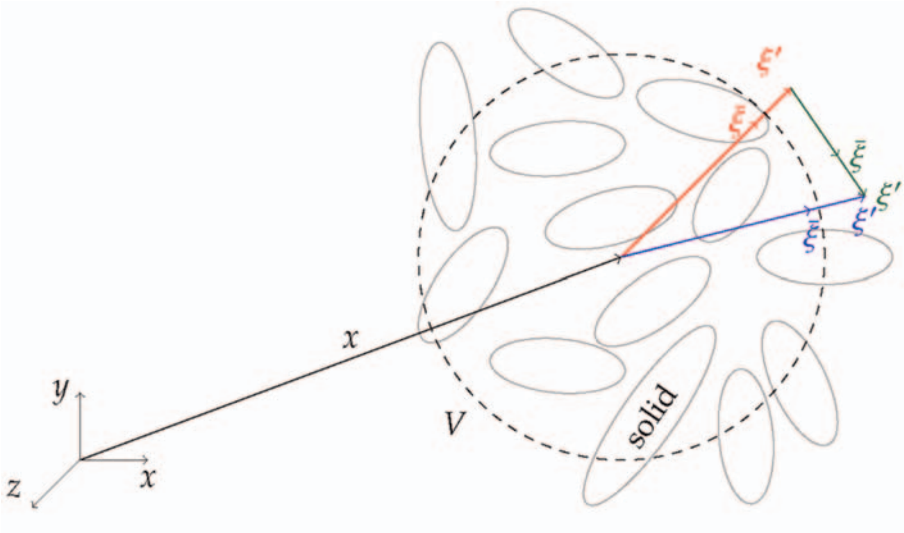

Figure 1.
REV shown as a circle (sphere) with dashed line, centered at $\mathbf{x}$.

2.2 k - ε model

Applying the decomposition approach leads to the inclusion of the Reynolds stress term in the governing equations. One way to model the Reynolds stress is by introducing the turbulent viscosity (μ_t). Several models have been developed, which are classified depending on how many equations are solved to estimate μ_t. This viscosity is related to the turbulent kinetic energy (k) and the turbulent kinetic energy dissipation rate ε that are necessary to solve the Reynolds Averaged Navier-Stoke (RANS) system equations. One of the simplest and widely used models is the k - ε model. The model, originally presented by Jones and Launder [24] to be applied in PM, requires introducing the porosity, obtaining the following transport equations [25]:

$$\rho\left[\frac{\partial}{\partial t}\left(\phi\langle k\rangle^i\right)+\nabla\cdot\left(\overline{\mathbf{u}}_D\langle k\rangle^i\right)\right]=\nabla\cdot\left[\left(\mu_t+\frac{\mu_{t\phi}}{\sigma_k}\right)\nabla\left(\phi\langle k\rangle^i\right)\right] -\rho\left\langle\overline{\mathbf{u}'\mathbf{u}'}\right\rangle^i:\nabla\overline{\mathbf{u}}_D+C_k\rho\phi\frac{\langle k\rangle^i|\overline{\mathbf{u}}_D|}{\sqrt{K}}-\rho\phi\langle\varepsilon\rangle^i \tag{12}$$

$$\rho\left[\frac{\partial}{\partial t}\left(\phi\langle\varepsilon\rangle^i\right)+\nabla\cdot\left(\overline{\mathbf{u}}_D\langle\varepsilon\rangle^i\right)\right]=\nabla\cdot\left[\left(\mu_t+\frac{\mu_{t\phi}}{\sigma_k}\right)\nabla\left(\phi\langle\varepsilon\rangle^i\right)\right] +C_{1,\varepsilon}\left(-\rho\left\langle\overline{\mathbf{u}'\mathbf{u}'}\right\rangle^i:\nabla\overline{\mathbf{u}}_D\right)\frac{\langle\varepsilon\rangle^i}{\langle k\rangle^i}+C_{2,\varepsilon}\rho\phi\left[C_k\frac{\langle\varepsilon\rangle^i|\overline{\mathbf{u}}_D|}{\sqrt{K}}-\frac{\langle\varepsilon\rangle^{i^2}}{\langle k\rangle^i}\right] \tag{13}$$

where the turbulent viscosity is defined by:

$$\mu_{t\phi}=\rho C_\mu\frac{\langle k\rangle^{i^2}}{\langle\varepsilon\rangle^i} \tag{14}$$

Solving these two transport equations together with the momentum equations makes it feasible to solve the mean flow without using empirical relations.

2.3 The thermal non-equilibrium model

The RANS equation for the heat transport is defined as follows:

$$\rho C_p \left(\frac{\partial \overline{T}}{\partial t} + \overline{u}_j \frac{\partial \overline{T}}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left[\left(k + \frac{k_t}{Pr_t} \right) \frac{\partial \overline{T}}{\partial x_j} \right] \tag{15}$$

However, this only works for a clear flow. When the flow includes a PM, it is necessary to consider another phenomenon, such as thermal dispersion, fluid–solid interaction, and tortuosity. To get the equations of the turbulent heat transport in PM, thermal local equilibrium can be assumed, which considers that the fluid in a solid matrix has the same temperature but is not successful when internal heat sources are non-uniformly distributed or high thermal gradients are produced. In this sense, a two-energy equation model considering thermal local non-equilibrium has been proposed [26]. This model distinguishes between fluid and solid temperature by the following equations:

$$\frac{\partial}{\partial t} \left((1-\phi)\rho_s c_s \langle \overline{T_s} \rangle^i \right) = \nabla \cdot \left(\mathbf{K}_{\mathrm{s,eff}} \cdot \nabla \langle \overline{T_s} \rangle^i \right) - h a_i \left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i \right) \tag{16}$$

$$\frac{\partial}{\partial t} \left(\phi \rho_f c_f \langle \overline{T_f} \rangle^i \right) + \nabla \cdot \left(\rho c_f \overline{\mathbf{u}}_D \langle \overline{T_f} \rangle^i \right) = \nabla \cdot \left(\mathbf{K}_{\mathrm{f,eff}} \cdot \nabla \langle \overline{T_f} \rangle^i \right) + h a_i \left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i \right) \tag{17}$$

where the effective conductivity tensor for the fluid and solid phases is given by:

$$\mathbf{K}_{\mathrm{s,eff}} = [(1-\phi)\lambda_s]\,\mathbf{I} + \mathbf{K}_{s,f} \tag{18}$$

$$\mathbf{K}_{\mathrm{f,eff}} = [\phi\lambda_s]\,\mathbf{I} + \mathbf{K}_{f,s} + \mathbf{K}_{disp} + \mathbf{K}_t + \mathbf{K}_{disp,t} \tag{19}$$

Each coefficient is defined as follows:

$$\text{Thermal dispersion}: \quad -(\rho c_f) \left(\phi \langle {}^i\overline{\mathbf{u}}\,{}^i\overline{T}_f \rangle^i \right) = \mathbf{K}_{disp} \cdot \nabla \langle \overline{T_f} \rangle^i \tag{20}$$

$$\text{Turbulent thermal dispersion}: \quad -(\rho c_f) \left(\phi \overline{\left\langle {}^i\mathbf{u}'\,{}^i T_f' \right\rangle^i} \right) = \mathbf{K}_{disp,t} \cdot \nabla \langle \overline{T_f} \rangle^i \tag{21}$$

$$\text{Turbulent heat flux}: \quad -(\rho c_f) \left(\phi \overline{\langle \mathbf{u}' \rangle^i \left\langle T_f' \right\rangle^i} \right) = \mathbf{K}_t \cdot \nabla \langle \overline{T_f} \rangle^i \tag{22}$$

$$\begin{aligned} \text{Local conduction}: \quad \nabla \cdot \left[\frac{1}{\Delta V} \int_{A_i} \mathbf{n}_i k_f \overline{T}_f dA \right] &= \mathbf{K}_{s,f} \cdot \nabla \langle \overline{T_f} \rangle^i \\ &= \mathbf{K}_{f,s} \cdot \nabla \langle \overline{T_s} \rangle^i - \nabla \cdot \left[\frac{1}{\Delta V} \int_{A_i} \mathbf{n}_i k_s \overline{T}_s dA \right] \end{aligned} \tag{23}$$

3. Applications

3.1 Combustion in porous media

The concept of enhanced combustion within a porous matrix or PMC originates in the idea of recirculating the energy from the reaction zone to the incoming reagents, aiming to reach higher temperatures and thermodynamic efficiencies in the process. In contrast to traditional combustion systems that take place in open spaces, PMC occurs within a highly porous solid medium, such as metal foams, refractory ceramics, or fibrous structures, which facilitates heat transfer between solid and gas phases.

In PMC, the propagation of the flame can be understanding as the interaction of two coupled waves: a thermal and combustion waves. Similar propagation speeds for these waves can produce the superadiabatic combustion temperatures (**Figure 2**), also known as the matching condition [28, 29]. Propagation of the combustion wave takes place at subsonic velocities (~ 0.1 (mm/s)) in the so-called low velocity regime [30], thus a method to detain or stabilize the combustion wave needs to be applied for continuous operation of the burner.

A dimensionless criterion for stabilization is the modified Péclet number, which is measured where the combustion wave propagates through two zones. When the $Pe_m \geq 65$, the flame can propagate, but if $Pe_m < 65$, the propagation is inhibited [31].

A dimensionless criterion for the stabilization is the modified Péclet number (Eq. (24)), which is measured where the combustion wave propagates through two zones. When the $Pe_m \geq 65$, the flame is capable to propagate, but if $Pe_m < 65$, the propagation is inhibited [31]. Adjusting the Péclet number to these values, by using two porous bodies with different thermophysical properties (commonly different d_p), the combustion wave is stabilized at the interface of the porous bodies due to local flame quenching.

$$Pe_m = \frac{S_L d_p \rho_f c_f}{\lambda_f} \tag{24}$$

Bubnovich et al. [32] conducted an experimental study on flame stabilization in a two-layer PM burner using reticulated alumina foam, honeycomb alumina foam, and SiC foam as porous ceramics. Their results indicated that the combustion wave propagation rate for all three ceramic materials increased with increased inlet velocities and decreased equivalence ratios of the premixed gases. Combustion temperatures ranged between 1160 and 1380 K, with higher flow rates leading to higher temperatures. Additionally, CO and NOx emissions remained below a few ppm, indicating that combustion was almost complete.

Micro-combustors are portable power devices that provide energy efficiently, where heat recirculation is a key factor influencing the combustion

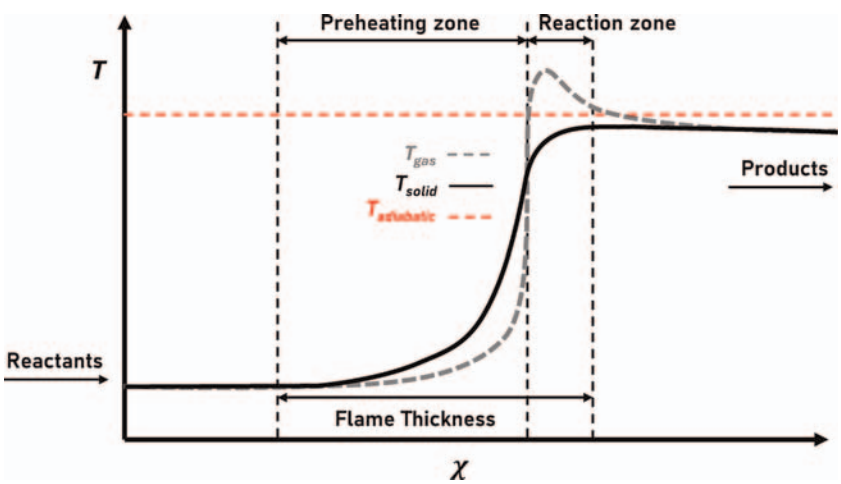

Figure 2.
Gas-and solid-phase temperature profiles in PM-based combustion. Adapted from Ref. [27].

process. Yan et al. [33] proposed a heat-recirculating micro-combustor embedded with PM to enhance heat recirculation and improve combustion stability. The results showed that micro-combustor embedded with porous media (MCEPM) improved the radial temperature uniformity and enhanced the preheating capability. When the embedding thickness was set to 15 mm, the combustor achieved an optimal balance between stable combustion and efficient heat recirculation.

Vignat et al. [34] evaluated the stabilization of NH_3/H_2/air flames using PM burners. The results showed that when operating the burner near its extinction limit, the NOx emission reaches a minimum level and tends to increase with increasing mass flux rates. In addition, due to the unburned NH_3 emissions remaining around 1400 ppm, this regime offers similar or better performance compared with the common fuel-rich operation.

Huang et al. [35] investigated numerically the methane-hydrogen combustion on a cylindrical double-layer porous burner geometry considering the effect of the temperature, combustion rate, and diffusion characteristics of the methane-hydrogen-precipitated gas flame within the PM. The authors noticed an accelerated flame diffusion within the porous combustion zone with an increase in the hydrogen blending ratio, leading to an enhanced combustion rate. Besides, the results showed that in the porous combustion section are located the high-temperature regions.

A swirler combustor is a combustion chamber that employs a swirler to induce a strong swirling motion in the flow. This action creates a low-pressure region near the burner, causing hot combustion gases to recirculate back toward the burner. This promotes ignition and flame stability [36]. Tolouei and Gharehghani [37] conducted a numerical study to evaluate the use of catalytic platinum PM in NH_3/H_2 fuel blends to improve the flame characteristics and reduce NOx emissions in a microscale swirl combustor. The results showed that a reduction in NOx emissions leads to 69% when the platinum catalytic is used compared to non-catalytic combustion. Moreover, increasing the porosity of the platinum PM from 0.4 to 0.8 led to a 50% decrease in NOx emissions during pure ammonia combustion, highlighting the effectiveness of catalytic PM in emission control.

In general, the PM has a homogeneous porous structure. However, in some cases, a gradual change of either porosity or pore size can exist along a defined axis called gradient PM [38]. Chen et al. [39]. proposed a gradient porous structural burner to investigate numerically the effects of pore size and porosity gradient on the combustion characteristics and stability limits of hydrogen-enriched natural gas flames. The results showed that the axial pore size increment structure improved the stability limit by approximately 117%, while the radial pore size increment structure increased the stability limit by 47% compared to the conventional two-stage uniform structure.

Unlike conventional burners, a porous radiant burner involves a fuel-air mix into the PM, stabilizing the combustion very close to the porous exit plane. The hot gases heated the PM, releasing energy as radiation [40]. Deb and Muthukumar [41] studied the air entrainment and flame stability through the geometrical dimensions of a Self-Aspirated Porous Radiant Burner of 5 kW capacity. The authors analyzed the effect of Orifice Position, Orifice Diameter, and Mixing Tube Diameter. The results showed a stable operation in a partially submerged combustion mode with an optimized setup featuring a 0.3 mm Orifice Diameter positioned 30 mm from the datum, coupled with a 29 mm Mixing Tube Diameter.

3.2 Enhanced heat transfer and waste heat recovery

Industrial waste heat (WH) is defined as heat rejected from industrial processes, in which energy is used to produce high-added value products. The most common ones are gaseous streams (e.g. exhaust gas, flaring gas, low-quality steam, cooling air), liquid streams (e.g., hot oil, cooling water), and solids (e.g., commodities and products, such as hot steel) [42]. The amount of WH as a fraction of energy consumption greatly varies among the various industrial sectors [43]. The temperature at which heat is available can vary over a wide range depending on the industrial sector and process, from around 50°C up to 1000°C or higher. This allows for exploring innovative thermal management strategies to maximize energy recovery efficiency. A promising approach involves the use of PM, such as metals, ceramics, or polymers, offering unique thermo-physical properties that make them highly suitable for enhancing heat transfer processes. Its high superficial surface and interconnected porous structure allow an efficient heat exchange through conduction and convection [44].

There are several heat recovery technologies, and one of them consists of heat exchangers (HX) that take heat from exhaust gases to transfer it to another fluid. Hossein et al. [45] considered a porous-filling technique to improve the heat transfer rate in a shell and tube HX. The researchers performed a numerical study to achieve a homogeneous thermal distribution by identifying a mechanism that manipulated the flow structures and heat transfer. The results showed a uniform thermal distribution in both porous-filled designs. In addition, they improved the heat transfer efficiency to 60% compared to the porous filled with a conventional type but with a high-pressure drop.

Bogdan and Abdulmajeed [46] investigated experimentally and numerically the effect of metallic PM, inserted in a pipe, on the rate of heat transfer. The pipe was subjected to a constant and uniform heat flux. The effects of ϕ, d_p, and thermal conductivity as well as Re_d number on the heat transfer rate and pressure drop were investigated. The results showed that higher heat transfer rates can be achieved using porous inserts at the expense of a reasonable pressure drop. But, the effective thermal conductivity is necessary for accurate simulation.

Scott et al. [47] addressed a transient analysis to solve the convective and conductive heat transfers based on a finite-element scheme. The model considered phase change aspects of a frozen medium through the latent heat effect. The model was validated against six test cases with known analytical solutions, such as (a) single-phase fluid flow through PM, (b) radial conduction with and without phase change, (c) conductive and convective heat transfer in an aquifer, and (d) two-phase immiscible flow in PM showing, in all cases, a strong agreement with analytical solutions.

Gao and Hodgson [48] studied computationally regenerator optimization and its operating parameters using unstable 3D flow and heat transfer. The heat exchange process in the regenerators and the effects of the regenerator structure and operating parameters such as gas mass flow, inversion time, regenerator height, sphere diameter, and thermophysical properties of the spheres were studied with the model to determine the efficiency of heat recovery.

Franklin and Ramesh [49] analyzed a Pebble Bed HX integrated with an internal combustion (IC) engine system, designed to recover heat from exhaust gases. In their study, a thermal energy storage (TES) unit was employed to store the energy generated during operation. It was found that nearly 9–12% of fuel power stored as heat energy in the combined storage system at a higher temperature can be used for suitable applications.

Xu et al. [50] presented a 2D steady model to investigate WHR in a sinter vertical tank based on the PM theory and the local thermal non-equilibrium (LTNE) model. The influences of the air flow rate, sinter flow rate, and sinter particle diameter on the gas–solid heat transfer process were investigated numerically. The results indicated that both heat dissipation and power consumption gradually increase with an increase in air mass flow rate. In contrast, increasing the sinter flow rate reduces heat dissipation, causing an increase in power consumption.

Lee et al. [51] conducted a numerical-experimental study of HX equipped with finned heat pipes, modeling the finned regions as PM using the LTNE approach. A computational framework that integrated Computational Fluid Dynamics (CFD) simulations with experimental validation achieve a WHR of 30.2 kW and a thermal effectiveness of 0.78. The model exhibited high accuracy in predicting heat transfer rates, with a maximum error of 6.2%, outperforming conventional Local Thermal Equilibrium (LTE) approaches, which tended to overestimate efficiency.

Another way to recover waste heat is through TES systems, which can store thermal energy at high or low temperatures. It is categorized into three kinds of systems depending on the state of energy: sensible, latent heat storage, or thermochemical heat storage [52]. Sensible heat storage represents the most economical form of thermal storage and has been performed using solid materials such as rocks, ceramics, and metals, among others [53]. Amiri et al. [54] conducted the feasibility of WHR by TES systems. The researchers used an exhaust gas inside a packed rock bed as a TES. The findings of this study reveal that, although the total thermal energy storage capacity of the system remains largely unaffected by variations in mass flow rate, operating at a lower mass flow rate extends the working period of the thermal energy storage system. On the other hand, a PCM is used to store latent heat. Yang et al. [55] considered a shell-and-tube thermal storage unit to simulate a two-dimensional axisymmetric natural convection employing an open-cell metal foam with a porosity of 0.94 and a pore density of 15 PPI in heat transfer fluid and PCM domains. The results showed that heat transfer can be enhanced if a metal foam is considered due to the reduction of thermal resistance in heat transfer fluid. In addition, the temperature uniformity of PCM can be improved if a metal foam is embedded.

Thermoelectric generators (TEG) are devices that convert the heat differential in voltage potential through the Seebeck effect [56]. **Figure 3** shows a representation of these thermoelectric generators. Donoso and Henríquez [58] used a PM burner to simulate the adiabatic recovery coupled with thermoelectric elements. Two semiconductors, n and p type, combined in series, form a thermoelectric unit. The authors observed that the increase in energy content of the mixture and duplicating the thermal conductivity contributes to reaching high values of electric potential, thermoelectric efficiency, and flame temperature.

Nithyanandam and Mahajan [59] studied exhaust systems using thermoelectric generators and investigated the performance of metal foam-based HX to reduce the thermal resistance of the hot side in thermoelectric generators. The authors found that the maximum net electric power is 5.7 to 7.8 times higher when a metal foam is used than when it is not. Choi et al. [60] investigated thermoelectric modules based on customized bismuth-telluride applied to the WHR of a diesel engine. A maximum efficiency of 2.83% was achieved using an optimal porosity of 0.416 at engine rotation of 1400 rpm. In contrast, at 1000 rpm, the conversion efficiency was optimized at 10.1% compared with a base case without PM. Donoso et al. [61] investigated numerically the WHR using hot air through a square section duct with spherical PM. A global efficiency was obtained in the range of 0.11–4.51%. Furthermore, increased fluid inlet

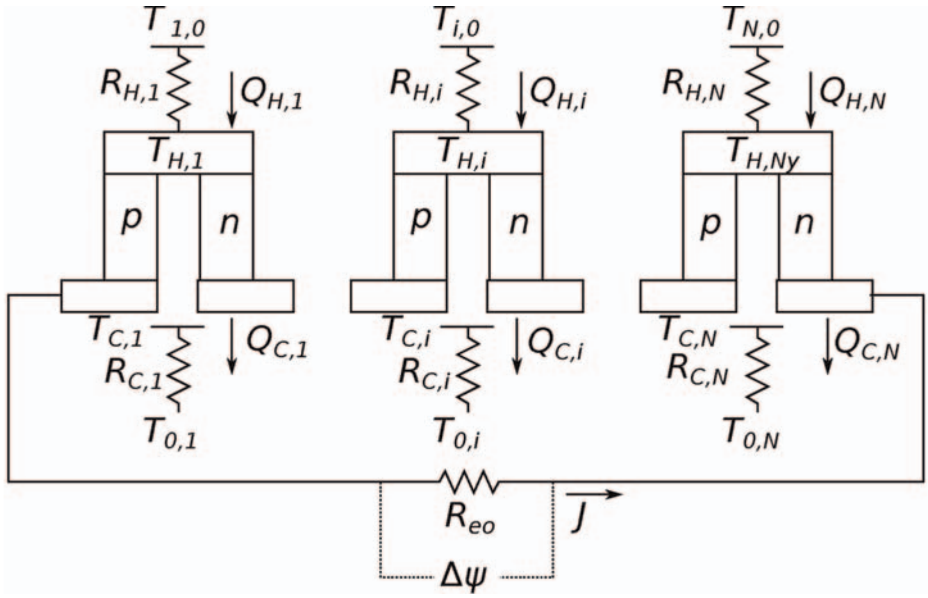

Figure 3.
Schematic representation of thermoelectric elements [57].

temperature and speed or a higher external heat transfer coefficient improved the system's performance.

Li et al. [62] investigated the impact of TDs and porous copper foam on TEGs. Through experiments and CFD simulations, they analyzed the insertion of foam into the central flow region with varying pore densities and volumetric ratios. The results showed that TDs with low thermal conductivity and high electrical conductivity increased power output by 230% compared to thermogenerators without foam. The model was validated with errors below 5.2%.

Li et al. [63] conducted a numerical and experimental study of a TD designed to recover WH from cables, evaluating the effect of fins filled with porous metal foam. Through CFD simulations and thermal analysis, they demonstrated that foams with high porosity (91.9%) and low pore density (10 PPI) enhance heat transfer by 20%, increasing the generated electrical power. They concluded that this design optimizes η_E by compensating for pressure drop losses and is feasible for practical implementation in energy systems.

3.3 Porous media combustion and thermoelectric generators

Micro-power generators are small-scale devices that capture energy from surrounding environmental sources and convert it into electrical energy [64]. These systems incorporate micro-combustion chambers, which encounter issues related to flame stability and energy efficiency [65]. Fu et al. [66] investigated the optimization of combustion performance and energy conversion efficiency of micro-power generator. The researchers evaluated the H/NH_3 blending ratio found that a small blended fraction of NH_3 significantly influences the flame regime of H_2/NH_3/air combustion. Besides, PM enhances flame stability, improving heat transfer within the combustion chamber.

Katsuki et al. [67] considered a reciprocating flow combustion for thermoelectric power generation to evaluate its performance. A reciprocatory flow of dilute fuel gas was introduced, and a 200 K/cm gradient was obtained. Despite using fuel mixtures normally not flammables, the system reached an energy density of up to 7 kW/cm^3.

Weinberg et al. [68] studied the maximum theoretical efficiency in regenerative burners. A novel configuration is proposed, which includes a two-stage heat rejection system: The first transfers heat to the incoming reactants, enhancing efficiency, while the second expels residual heat to the ambient environment. These devices significantly exceed the maximum efficiency of current thermoelectric conversion systems.

Hanamura [69] proposed a novel power generation system based on reciprocating-flow super-adiabatic combustion within a catalytic and thermoelectric porous element. The authors established a trapezoidal temperature profile, which result in a temperature gradient in the thermoelectric porous element. Through numerical evaluation, the heat transferred reached 94% through the thermoelectric element by conduction.

Bubnovich et al. [70], based on super-adiabatic combustion, proposed a conversion combustion heat system into electric power. The numerical results showed a total thermal efficiency of 4.6%, equaling the thermoelectric element's conversion efficiency.

Bubnovich et al. [71] proposed a combustion-based system for generating electricity using a thermoelectric porous element. Numerical simulations showed that using leaner mixtures and higher combustion wave propagation velocities increases the overall thermal efficiency, approaching the thermoelectric element's conversion efficiency.

Henríquez-Vargas et al. [72] studied numerically a continuous flow PM burner for the direct conversion of thermal to electric energy. The results showed that there is an optimal length and placement region for the thermoelectric elements within the step thermal gradients, which maximizes power output.

Ding et al. [73] developed a thermoelectric system based on PM microcombustors to enhance energy conversion in Micro-Electro-Mechanical Systems. The results showed that, under low equivalence ratio mixtures and high flow rates, a maximum η_E of 5.51% was achieved, while mixed-fuel combustion increased the power output to 57.8 W. The optimization used segmented materials (Bi_2Te_3/PbTe) and enhanced thermal conductivity, emphasizing the importance of thermal uniformity.

Yan et al. [74] investigated a two-stage thermophotovoltaic-thermoelectric system incorporating PM to enhance energy efficiency in microcombustion. Through numerical simulations was observed a power output of 14.88 W and an η_{E} of 7.33%. The study highlights the importance of thermal uniformity and parameter selection in energy recovery systems.

4. Challenges and trends

4.1 Combustion in porous media

PMC offers several advantages that highlights its capacity to improve the thermal efficiency due to the unique structure of PM, allowing better fuel utilization and lower operational losses. Another key aspect is the reduction of pollutant emissions due to the stabilization of the flame within the PM and its subsequent heat distribution, which promotes a more complete and homogeneous combustion virtually free from cold/hot spots that generate CO/NOx contaminants. Moreover, it is compatible with WHR technologies, such as TEGs, expanding its potential in advanced thermal systems. However, the transition of the PMC to industrial or commercial scales faces several technical and physical challenges. Modeling such systems involves complex multiphase flows across multiple scales (from the pore level to the macroscopic level), significantly increasing computational demands. Additionally, the Péclet number becomes a critical parameter in determining whether combustion can be sustained, relating to flame stabilization and a minimum pore size threshold. Poor fuel mixtures or high inert gas contents can further complicate ignition and propagation. Furthermore, due the higher temperatures reached, the porous material is degraded and/or its physical properties changed (such as thermal expansion giving high mechanical stresses, others), affecting the long-term stability and performance of the system. Complementary, in real implementations of PMC burners, it may be necessary to perform maintenance of the equipment—and porous bed—which may be troublesome. In particular applications for household users (stoves), there can be cultural barriers presented by the use of (diffusive) free flame conventional systems that need to be overcome. To address these challenges, continued development of accurate, scalable models, systems and advanced materials is essential to consolidate PMC as a key tool in the energy transition.

4.2 Waste heat recovery

WHR technologies have gained prominence in recent years, achieving integration into a wide range of applications, from HXs, power generation, industrial furnaces, and internal combustion engines. Combined with the advanced materials, WHR systems can significantly increase heat transfer rates and overall energy recovery. However, despite their potential, they still present several challenges that can be addressed by designing materials that are resistant to degradation and offer high chemical stability and high mechanical strength, and that generate reasonable pressure drops, resulting in lower costs per fluid drive. One limitation of the use of PM is the variability of WH conditions in terms of temperature and chemical composition of the fluids. A decrease in temperature can generate undesirable conditions such as moisture condensation and sulfuric acid production in flue gases from diesel-powered industrial boilers. This makes it difficult to develop a comprehensive system where each thermal solution is tailored to each specific case, and the initial implementation cost and the return-on investment may pose barriers for small- and medium-sized industries, which limits large-scale adoption. The development of porous materials such as Metal–Organic Frameworks (MOFs), Covalent Organic Frameworks (COFs), and Polymers of Intrinsic Microporosity (POPs) that offer high selectivity, recyclability, and thermal and chemical stability, can be explored as specific alternatives in WHR processes through neural network-assisted modeling, the generation of porous structures with machine learning or other forms of artificial intelligence (AI) assistance. Continuous advances in functional materials, such as metallic foams or porous ceramics, and advances in direct conversion technologies, such as high-performance TEGs, are expanding the application possibilities which can be extended to non-conventional renewable energy systems, promoting energy sustainability and the circular economy.

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Nomenclature

a_i	specific surface (m^2/m^3)
A_i	interface area between the fluid and the solid phases (m^2)
C_μ	turbulent model constant
$C_{1,\varepsilon}$	turbulent model constant
$C_{2,\varepsilon}$	turbulent model constant
C_k	turbulent model constant
c_f	fluid specific heat (J/kg^{-K})
c_s	solid specific heat (J/kg^{-K})
h	convective heat transfer coefficient (W/m^2K)
k	turbulent kinetic energy (m^2/s^2)
$\mathbf{K}_{eff}$	effective conductivity tensor (W/m-K)
$\mathbf{K}_{disp}$	conductivity tensor due to dispersion (W/mK)
$\mathbf{K}_{f,s}$	local conduction tensor (W/m-K)
$\mathbf{K}_{disp,t}$	conductivity tensor due to turbulent dispersion (W/mK)
$\mathbf{K}_t$	conductivity tensor due to turbulent heat flux (W/mK)
$\mathbf{I}$	tensor unit
$\mathbf{n}_i$	unit vector
p	pressure (Pa)
$\mathrm{Pr_t}$	Prandtl turbulent number
$\mathrm{Pe_m}$	modified Peclet number
Re_d	pore-based Reynolds number
S_L	laminar stoichiometric flame speed (m/s)
T	temperature (K)
$\mathbf{u}$	velocity (m/s)
$\bar{\mathbf{u}}_D$	Darcy velocity (m/s)

Greeks

ε	dissipation rate of k
ΔV	elementary volume (m^3)
ΔV_i	fluid volume in ΔV (m^3)
ϕ	porosity
μ	viscosity (kg/ms)
$\mu_{t\phi}$	macroscopic coefficient of exchange for porous media (kg/ms)
ξ	generic property within porous media
λ	thermal conductivity (W/mK)
ρ	density (kg/m^3)
σ	turbulent model constant

Subindex

i	phase index
f	fluid phase
s	solid phase

Operators

$\langle\cdot\rangle$	volume average
$\langle\cdot\rangle^i$	intrinsic volume average
$^i\cdot$	spatial perturbation
$\bar{\cdot}$	time average
$\cdot'$	time perturbation

Abbreviations

CFD	computational fluid dynamics
HX	heat exchanger
PCM	phase change material
PM	porous media
PMC	porous media combustion
PPI	porous per inch
RANS	Reynolds averaged Navier-Stoke
REV	representative elementary volume
TEG	thermoelectric generators
TES	thermal energy storage
WH	waste heat
WHR	waste heat recovery

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