CHAPTER 2 THEORY

2.1 Self-aspirating gas burner

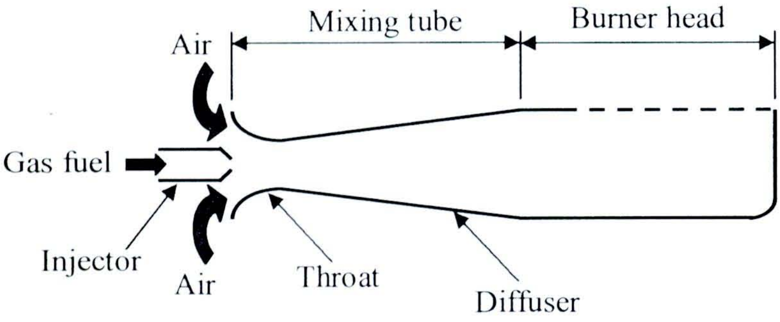


Figure 2.1 The general layout of self-aspirating gas burner [27].

Figure 2.1 shows schematically the basic design of a typical aerated burner. Gas emerges from an injector nozzle consisting of one or more small holes. On leaving the injector, the gas entrains primary air by a momentum-sharing process between the emerging gas and ambient air. The gas/air mixture enters a mixing tube, which may be shaped in the form of a tapered venturi or may have parallel sides. As its name suggests, the mixing tube is designed to ensure thorough mixing of gas and air, such that a constant air/gas ratio is maintained throughout the burner head; the mixture must then be distributed uniformly to the burner ports. Optional features include an aeration shutter or mixing tube restrictor which controls primary air entrainment, and baffles or gauzes within the burner body which aid good mixing and prevent lint from clogging the burner ports. Examples of burners include drilled bar burners (such as those used in cooker ovens and grills), box burners (boilers and space heaters), circular cooker hotplate burners, jetted burners consisting of an array of small individual aerated burner jets screwed into a manifold, and a number of other variants.

The key of combustion in self-aspirating burner is an air entrainment or primary aeration. The basic air entrainment mechanism may be described by reference to figure 2.1. The gas stream emerges as a free jet from the orifice at a rate dependent on gas pressure, orifice dimensions and gas composition. Momentum transfer occurs between the jet and the surrounding air, resulting in entrainment and expansion into the entrance of the mixing tube. It is normally assumed that, owing to turbulence, mixing is virtually complete at the throat, at which point, depending on the precise geometry, the static pressure of the gas/air stream maybe reduced to almost that of the surrounding atmosphere. Further downstream, the static pressure must increase sufficiently to overcome resistances to flow within the burner and at the flame ports. A pressure increase can only be induced by a decrease in momentum and velocity, and this can only arise from a gradual expansion within the mixing tube. It is normally achieved by a suitably shaped diffuser section in the burner. The gas/air mixture then flows into the burner head prior to discharge from the flame ports.

2.2 Heat recirculation combustion

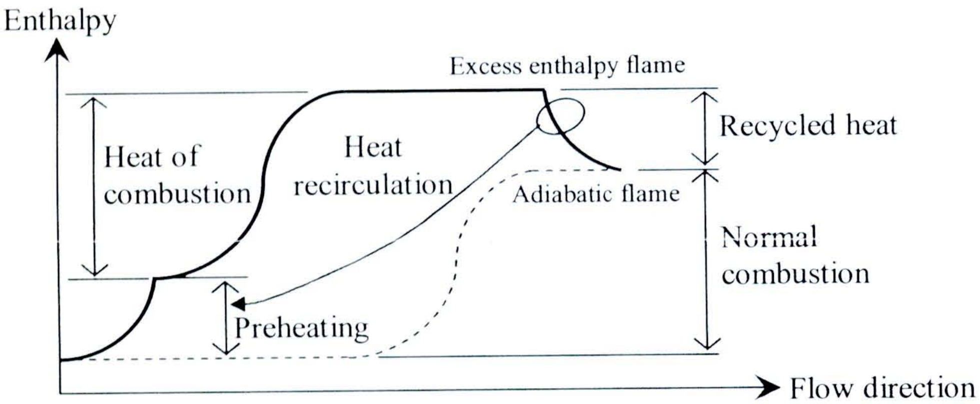


Figure 2.2 Concept of heat recirculation [20].

Heat-recirculating combustion is an effective technology not only for combustion of low calorific fuels but also for fuel conservation. Reactants are preheated prior to the flame zone by recycled heat from hot products.

Weinberg et al. [20, 28-30], proposed the concept of "borrowed" enthalpy from the combustion products to preheat the combustible mixture. The schematic temperature profiles in heat recirculating combustion of premixed reactants in one-dimension adiabatic system are compared in figure 2.2 for the case with and without heat recirculation. For normal combustion without preheating (dash line), the initial unburnt premixed reactants is ambient temperature. Combustion heat release raises the temperature to the adiabatic flame temperature, which depend on quality of mixture, thereafter remaining constant. While the initial reactants and flame temperatures in case of heat-recirculating combustion (bold line) are higher than normal combustion flame.

Because the additional enthalpy having been "borrowed" from the products are used to preheat reactant before entering to the reaction zone. The flame temperature in heat-recirculating combustion is determined by the amount of recycled heat that is independent of the equivalence ratio of mixture. Accordingly, it has been held that heat-recirculating combustion brings a temperature rise throughout combustion processes in proportion to the amount of recycled heat.

2.3 Reduction of energy consumption by air preheating

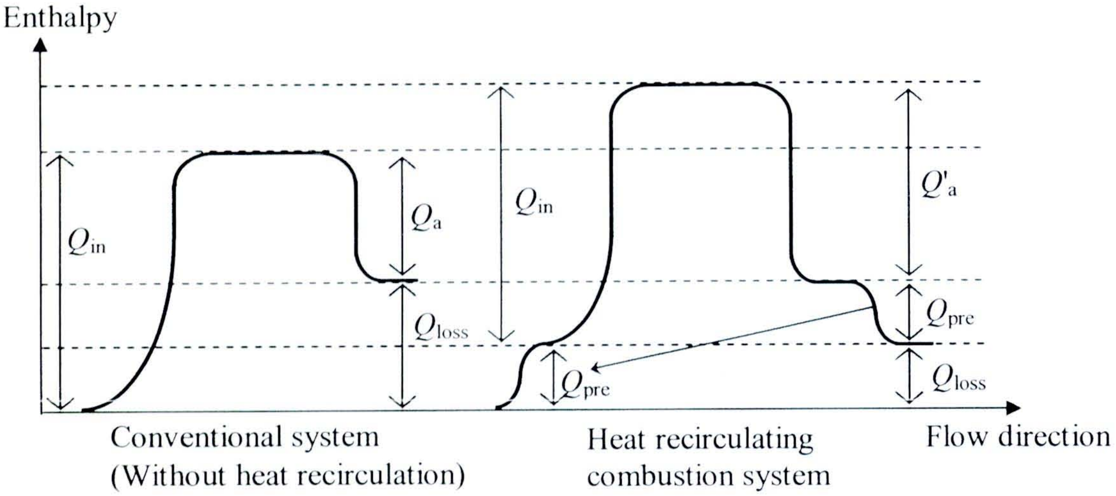


Figure 2.3 Enthalpy histories between systems with and without heat recirculation [6].

From figure 2.2, we can separate the system into two cases that are a conventional system and heat recirculating system, as shown in figure 2.3. Preheating of combustible mixture by recycled heat from exhaust gas has been considered as an effective method not only for combustion of low calorific fuels but also for fuel conservation. This type of combustion has been called "excess enthalpies" or "super-adiabatic flame temperatures" combustion in which the reactants (or the combustion air alone) are preheated using heat "borrowed" from beyond the flame zone, without mixing the two streams [20]. Although the principle is not sophisticated, the consequences of its application can be quite far reaching and very advantageous from the point of view of fuel conservation, efficiency and combustion intensity. The enthalpy histories of premixed combustion in a one-dimensional adiabatic system are schematically compared in figure 2.3 for cases with and without heat recirculation. In the presence of heat recirculation from the exhaust gas to the combustion air, Q_{pre}, with constant heat input, Q_{in}, a greatly elevated enthalpy (and, of course, the flame temperature) and hence useful energy Q'_a (larger than Q_a) can be realized, leading to energy saving as defined by Eq. (2.1)

$$\text{Energy saving} = \frac{Q_{pre}}{Q_a + Q_{pre}} = \frac{\eta_{th,2} - \eta_{th,1}}{\eta_{th,2}} \tag{2.1}$$

where $\eta_{th,1}$ and $\eta_{th,2}$, respectively, represent the thermal efficiency of the system before and after introducing the heat-recirculating combustion. Figure 2.4 shows the typical effect of combustion air preheating, $T_{air,pre}$, on energy saving (and, of course, substantial reduction in CO_2 emissions) at various operating exhaust gas temperatures, T_{ex}, from the exit of the furnace section (before entering a heat exchanger). The higher $T_{air,pre}$ ensures less rejection of heat with the exhaust, resulting in more fuel saving. Operating the combustion process at relatively high exhaust gas temperature with constant $T_{air,pre}$ is more efficient than operating at lower T_{ex}.

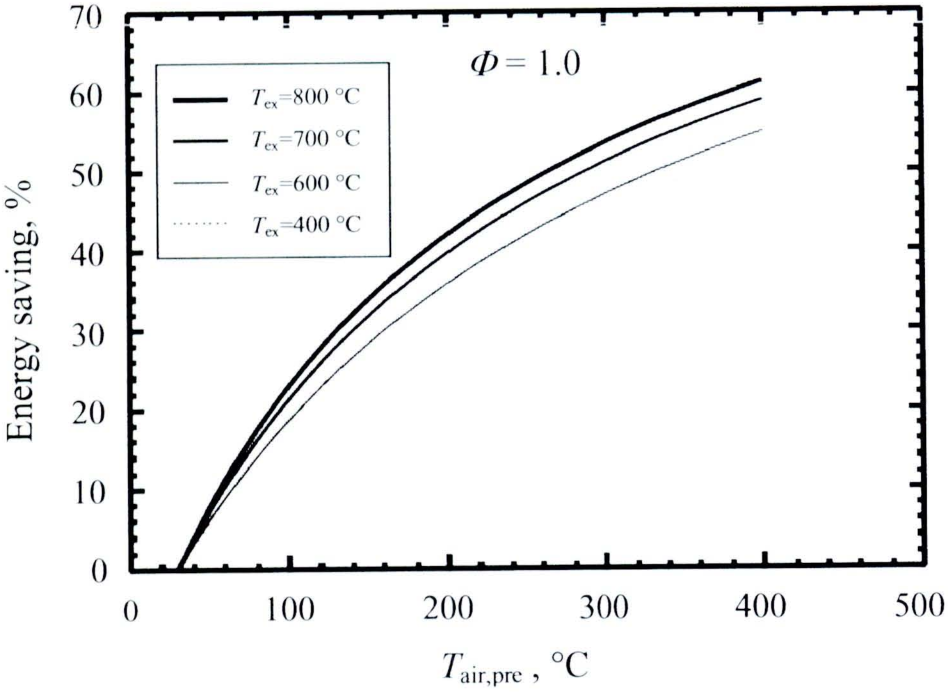


Figure 2.4 Effect of preheating air temperature on energy savings [6].

2.4 Effective method for combustion air preheating

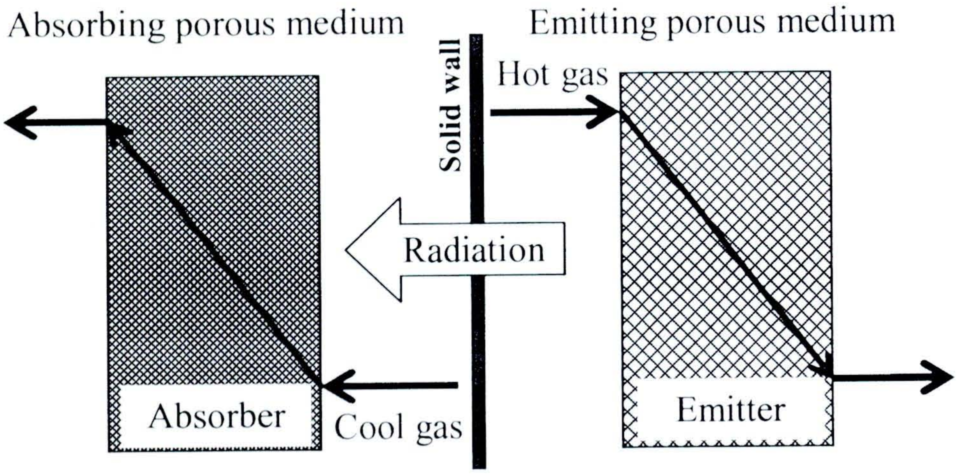
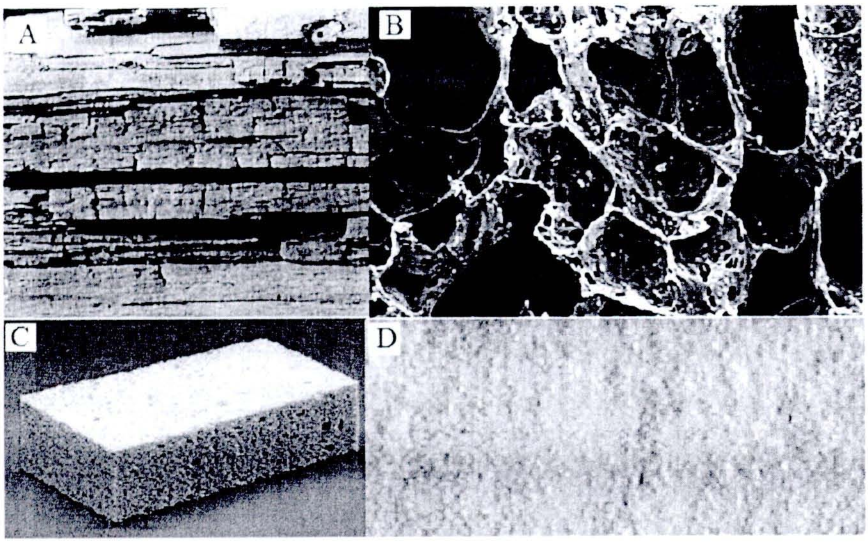


Figure 2.5 Porous medium heat exchanger [6].

A great variety of systems is possible for combustion air preheating that all based on a combustor in-between the two limbs of a heat exchanger [30]. However, it would seem retrograde to develop a new practical combustion system, which does not involve a porous medium, having a large surface area per unit volume, for an effective heat exchanger to recirculate heat from hot products to combustible mixture (or purely air). Based on the prominent feature of the porous medium in effectively converting energy between flowing gas enthalpy and thermal radiation, the development of a high performance heat exchanger using a porous medium was proposed by Echigo [31-32]. The basic concept consists of a pair of porous mediums with appropriate opacity separated by a solid wall as shown in figure 2.5. Enthalpy of the hot flowing gas (combustion gas products or exhaust gas), a red line in emitter, is effectively converted to thermal radiation emitted by the high temperature (heating) side porous medium designated as the "emitter" and directed to the solid wall. In thermal equilibrium, the reversed conversion from the incident thermal radiation emitted from the solid wall to the cool gas (or combustion air), a blue line in absorber, enthalpy takes place in the low temperature (cooling) side porous medium designated as the "absorber", leading to an efficient method in preheating the combustion air. Jugjai and Rungsimuntuchart [6] used this technique to develop a heat exchanger for the CB that can be enhances the thermal efficiency of the CB.

2.5 Porous Material



A. Wood; B. Human lung; C. Sponge; D. Sandstone.

Figure 2.6 Examples of porous materials.

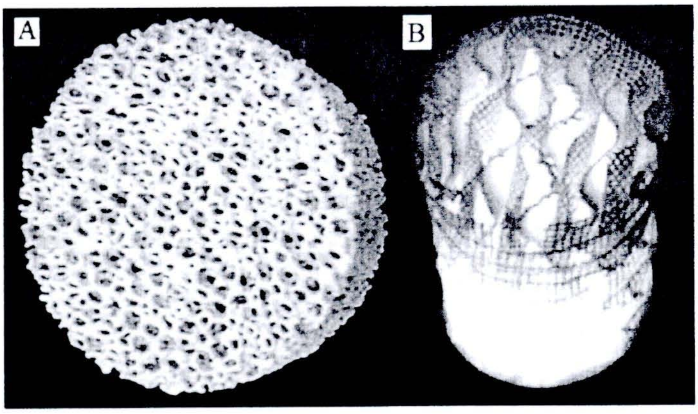
A porous medium is a material consisting of a solid matrix with an interconnected void. Examples of porous media are wood, human lung, sponge, and sand stone, as shown in figure 2.6. However, the porous media using in combustion, must be a relatively high temperature resistance material and its durability suffers from cracking caused by the stress of differential expansion experienced during startup and shutdown. Example of porous materials using in combustion field are SiC, Al_2O_3, ZrO_2 and YZA. Reticulated foam made of ZrO_2 and Lamella structure made of Al_2O_3 fibbers are shown in figure 2.7. A large number of researches in field of porous media are reported but the scope of this topic is only in combustion applications.

A combination of base material type and porous structure is important design consideration of porous burner that determines the combustion performance, the longevity and the system's versatility [33]. Ceramic materials are popularity used as porous burner because ceramic materials have a good temperature resistance; their durability suffers from cracking caused by the stresses of differential expansion experienced during startup and shutdown [34]. Alumina oxide (Al_2O_3), zirconia oxide (ZrO_2), and silicon carbide (SiC) are the most important based-materials are used. Other ceramics and high-temperature metals have only been occasionally employed [33]. All of porous materials based are substantially different with regard to manufacturing and properties.

Aluminum oxide (Al_2O_3, alumina, corundum) is a chemical compound of aluminum and oxygen, and is the most widely used inorganic chemical for ceramics and is produced from the mineral bauxite using the Bayer process [35]. Al_2O_3 is often used in combustion applications because of its high hardness, high chemical resistant, and high temperature resistant. Alumina-based materials have and intermediate thermal conductivity, thermal expansion resistance to thermal shock, and overall emissivity. Al_2O_3 is presently the lowest-cost high performance ceramic because of the large quantity produced [36]. Moreover, Al_2O_3 has been employed in a variety of porous structures, i.e. packed bed of Al_2O_3 ball, cellular foams, and fiber lamellae.

Zirconium dioxide (ZrO_2, zirconia) is principally derived from zircon, ZrSiO4, which occurs in igneous rocks such as granites and pegmatite [35]. ZrO_2 is an inorganic metal oxide that is mainly used in ceramic materials. Zirconia-based materials show excellent high temperature resistance, but very low thermal conductivity and thermal shock resistance. Because of the poor heat transport and thermal shock resistance, the uses of zirconia media in recent porous burner applications are limited [33].

Silicon carbide (SiC) is a chemical produced from the one-to-one binding of carbon (C) and silicon (Si), and is the most widely used non-oxide ceramic. Its major application is in abrasives because of its hardness. Silicon carbide does not occur in nature and therefore must be synthesized [35]. SiC-based materials can be used at a maximum temperature of about 1650°C. It is more resistant to chemical corrosion, such as oxidation, than other non-oxide ceramics; consequently, it is used for crucibles, parts for kiln burning, mechanical seals, and parts materials to produce semiconductors. Silicon carbide shows a high thermal conductivity, very low thermal expansion, and very good resistance to thermal shock [36].



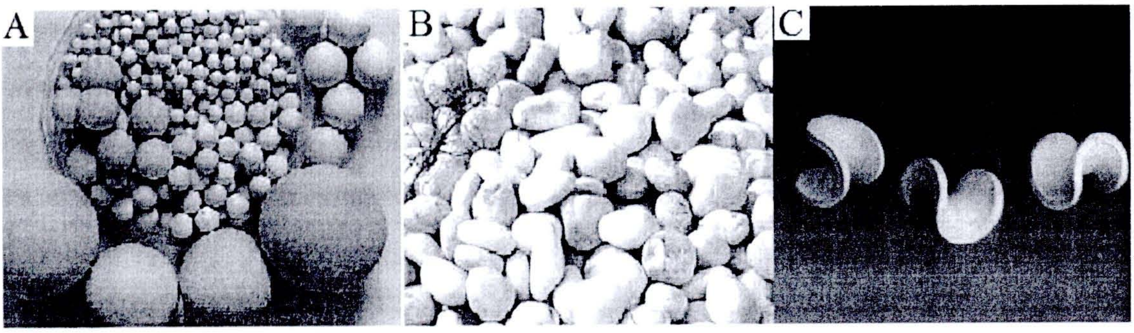
A. Reticulated foam made of ZrO_2; B. Lamella structure made of Al_2O_3 fibbers.

Figure 2.7 Examples of porous structures.

2.6 Porous Structures

2.6.1 Discrete elements

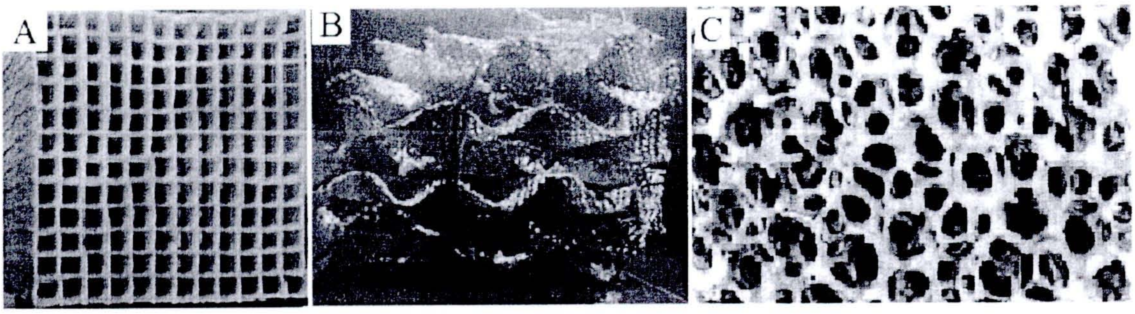
A number of porous burner investigations are created from discrete elements making up a packed bed. An advantage of discrete elements over cellular structure is that they are quite durable since they are not constrained in a rigid matrix and they have a robust shape. The main discrete element media used in published porous burner research are ceramic balls, ceramic pebbles and ceramic saddles [33]. A packed bed of uniform diameter spheres typically has porosity in the range of 0.2595 to 0.4764 [37]. Some discrete element media are shown in figure 2.8.



A. Ceramic balls; B. Ceramic pebbles; C. Ceramic saddles.

Figure 2.8 Discrete elements.

2.6.2 Cellular structures



A. Honeycomb shape; B. Lamellar structure; C. Reticulated ceramic foam.

Figure 2.9 Porous ceramics.

Cellular ceramics, also named ceramic foams or porous ceramics, offer a series of unique properties because of their combination of highly porous cellular structure and tailored composition of strut material. The ceramic foams are manufactured in variety shapes, for example honeycombs, lamellar structure, reticulated ceramic foam (refer figure 2.9). Ceramic foams are widely used for porous burners because of good conductivity heat transport, a rather long start-up phase due to lower macro-porosity, intermediate radiative heat-transport properties, intermediate dispersion properties, and relatively high pressure drop [36].

Typical monolithic structures have low porosity, low thermal conductivity and limited radiative heat transfer. The monolithic structure is suitable for the preheat zone of a porous burner because this structure can be reduced the risk of flame flashback [33].

2.7 Porosity of porous medium

The porosity of a porous medium, ε, is defined as the fraction of the total volume of the medium that is occupied by void space [37] or the porosity is the volumetric void fraction of the material [34]. In the other word, the porosity is the pore volume divided by the total volume occupied by the porous medium. Thus $1-\varepsilon$ is the fraction that is occupied by solid. The porosity is very important physical properties of porous medium, affect mechanical and thermal properties. Many correlations of effective thermal conductivity, volumetric heat transfer coefficient, elasticity, and pressure drop of porous medium are commonly based on the porosity.

Surface porosity, which is the fraction of void area to total area of a typical cross section, will normally be equal to ε for an isotropic medium. The porosity does not normally exceed 0.6 for natural media. If the packed bed consist of uniform diameter solid spheres, ε is in the range between 0.2595 (rhombohedral packing) and 0.4764 (cubic packing). Porosity of non-uniform grain size will smaller than in case of uniform grains, cause to smaller grains fill the pores formed by larger grains. For man-made material materials ε can approach value 1.

The porosity of porous medium can be measured by dividing the total volume of water extruded from a solid within porous structure:

$$\text{Porosity} = \frac{\text{Volume of water}}{\text{Volume of porous}} \tag{2.2}$$