Heating Systems, Plant and Control

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1 Introduction

1.1 Heating: the fundamental building service

Climates vary significantly around the world. Some regions experience sharp swings from summer to winter, whereas others are more temperate and have less severe variations. In many regions of the world buildings will require space heating systems to make them habitable. This is true even of buildings in which the predominant need, year-round, is for space cooling. A heating system is therefore *the* fundamental element of any building services strategy for providing thermal comfort. Whatever other facilities are required for a building to be occupied, none of these are much use if the heating system fails at low ambient temperature. Furthermore, beyond space heating itself, few of us would nowadays be willing to accept working in an environment in which hot water was not more-or-less readily available for sanitary and domestic use. This water must be heated, by one means or another, whether this be the same that is used to heat the spaces within the building or by independent means.

1.2 Low-pressure hot water

While a variety of means may be employed to provide the space and water heating that buildings typically need, none have so far proved quite as flexible and effective as systems based on the use of low-pressure hot water (LPHW), generated by a heating plant comprising one or more boilers. This is not, of course, to suggest that all LPHW heating systems *are* uniquely flexible and effective in every application. In such an arrangement the LPHW is used as a heat transfer medium, and is typically generated by the combustion of natural gas or fuel oil in the boilers. While medium-pressure hot water (MPHW), high-pressure hot water (HPHW) and steam have also been employed as heat transfer media, the cost, complexity and health and safety issues associated with their use will typically mean that they will only be considered in the rare commercial heating applications in which the sheer size of the heating loads make it either economically advantageous or technically essential. They will be more commonly found in industrial process heating applications where high temperatures must be attained and the health and safety issues may be more effectively accommodated.

Therefore, if heating is the fundamental element of building services HVAC systems, boiler-based LPHW systems represent the most fundamental form of heating employed in a wide range of commercial, public, institutional, educational, healthcare, retail and residential buildings, hotels and leisure facilities.

The fundamental element of any heating system is a means of generating heat, and in the case of LPHW heating systems this invariably, though not *exclusively*, takes the form of a boiler plant comprising one or more individual boilers. While very many buildings can operate quite satisfactorily without refrigeration or air handling plant, in practice few can work effectively without a boiler plant of some kind.

Once the heat has been generated, it must then be distributed around the building to the heat emitters. The heat emitters are the interface between the heating system and the occupants and determine the thermal comfort of the latter. ‘Radiators’ are, of course, the most common form of emitter in use for many building types (other than industrial), having a good reputation for thermal comfort, and their massive production has resulted in low cost. However, changes in building construction standards and the increased rental value of floor space in commercial buildings may make other forms of emitter preferable.

Achieving thermal comfort also requires a controllable heat output rate. This involves the design of a control and distribution system which can respond quickly and effectively to changes in heating demand. The second part of this book is concerned with the analysis of heat emission, distribution and control. This book is aimed particularly at non-domestic heating and hot water systems. However, many of the principles discussed will relate to domestic systems. Simple domestic systems are often a good starting point to explain the fundamental operation of more complex systems.

1.3 The need for efficient heating systems

Creating the levels of thermal comfort that we have come to expect of our public and private built environments consumes a prodigious amount of energy, virtually all in the form of fossil fuels. Currently natural gas is the favoured boiler fuel for new installations, or LPG where this is not available, although fuel oil continues to be used as well. Apart from any consideration of the economic cost of all of this gas and oil, their use contributes massively to the emission of carbon dioxide into the atmosphere. Indeed, in the UK and Northern Europe, heating systems are the single largest contributor, higher than transport or industry.

Even where good practice is employed in the design of efficient and effective space and water heating systems, a modern office building may annually consume some 100 kWh of fossil fuel per m^2 of treated floor area[1]. As each kWh of natural gas burnt in a boiler produces typically 0.19 kg of carbon dioxide, (0.052 kg carbon equivalent), this results in 19 kg of carbon dioxide per m^2 being emitted into the atmosphere each year, (or 5.2 kg carbon equivalent). This level of emission will be increased by some 35–40% if the boiler is fired on fuel oil.

Add to this that quantities of oxides of nitrogen (NO_x) are also emitted for each kWh of boiler fuel burnt. These too are greenhouse gases, with nitrous oxide being some 310 times more powerful in its global warming effect than carbon dioxide. There is increasing concern that NO_x emissions are also detrimental to health, with possible links to childhood asthma. At even the low level of emission of 70 mg NO_x kWh^{-1} for natural gas burnt in a modern boiler, 100 kWh releases 7 g of NO_x, equivalent to nearly another 2.2 kg of carbon dioxide. (Some boilers may emit two to three times this level of NO_x.) Studies in the early-to-mid 1990s put the UK stock of private-sector office space alone at some 275 000 buildings totalling over 72.5 million m^2, with public-sector offices and industrial buildings increasing this substantially to c.90 million m^2, and retail space alone more than doubling this total[2,3]. This pales into insignificance, of course, with the floor area of some 20 million dwellings.

The building services industry is therefore responsible for a large environmental liability, and has a duty to ensure the lowest environmental impact from systems that it installs. However, perhaps the most sobering thought for readers of this book as building services engineers is that the figures for energy consumption considered above represent the *good practice cases*. It may (or may not always!) be reasonable to assume that these performance levels are now routinely achieved in new buildings. Yet the 'typical' cases that represent much of the existing building stock may contribute twice as much emission of carbon dioxide and NO_x per m^2 floor area.

Viewed in this light the importance of ensuring that new buildings do indeed possess efficient and effective heating systems is clear, and that wherever possible the standard of existing installations is brought up to current standards of good practice when significant modification or refurbishment works are carried out. As in many disciplines, one of the keys to achieving improved performance of heating systems is a thorough understanding of both the theoretical and the practical issues involved in their design, installation, operation and control. The aim of this book is to provide that understanding.

1.4 Scope of the book

This book examines the key components of building heating systems, with an emphasis on how to select plant and design distribution circuits and controls to provide good indoor comfort conditions while minimising energy consumption. There are a number of texts that deal with the design and sizing of heating systems. These often focus on the procedures for heat loss calculations and pipe sizing, an essential part of design, yet they rarely explore the bewildering range of equipment available today, nor the operational implications for various design decisions, nor do they look at the complex dynamics of systems in use.

This book attempts to fill this gap, and is aimed at both experienced practitioners and students of building services engineering alike. It assumes a basic knowledge of heating systems design – steady state heat loss, pipe and pump sizing, the principles of control – and builds on this to facilitate a deeper understanding of how systems work in practice.

Much of what we understand about heating systems is based on common sense and day-to-day familiarity with heated buildings; however, there are many elusive questions that standard theory and practices cannot answer: what is the best boiler for a particular application, what is the relationship between energy and boiler firing patterns, what is the best emitter control strategy? The answers are not straightforward, but with a bit of practical analysis it is possible to select plant and controls that will best suit a particular application, and minimise the risk of failure or sub-standard performance.

1.5 Content of the book: an overview

The book is divided into two parts. Part A deals with the heat generating components of the central plant – boilers and flues, as well as various alternatives; part B deals with system design and control – emitters, system and central plant arrangements, efficient operation and energy performance. These areas have not been brought together before so comprehensively, and in order to deal with them in depth some of the fundamentals have been left out of the book where they are adequately dealt with in existing publications.

The reader is encouraged to refer to these where necessary. A brief outline of the chapters in this book is given below.

Part A deals with the heat generating equipment. Chapter 2 looks at low-pressure hot water (LPHW) boilers and burners from a generic perspective. The chapter opens with a brief consideration of how a boiler may be defined, and then sets out principal functional elements of gas-fired and oil-fired boilers, with particular regard to function, characteristics and general design. The function of the *boiler block* is explained, with a discussion of how heat transfer is maximised. Issues such as temperature rise across a boiler and the implications for low water content boilers are also dealt with. Burner function, combustion processes and fuel types are introduced, and specific attention is given to atmospheric and forced-draught natural gas burners and atomizing fuel oil burners. The control of boilers is introduced here in preparation for more detailed coverage in Chapter 10.

Chapter 3 looks at the types of LPHW boiler that may be encountered in modern commercial building services space and water heating applications. Types of boiler, and the materials used in their construction, are reviewed, with explanations of why typical boiler types are used in specific applications. This is extended to the appropriate use of single, multiple and modular boilers. The chapter also examines the principles, benefits and requirements of condensing operation and the design of condensing boilers. Boiler efficiency is defined, in terms of both gross and net calorific value, and the concepts of carbon intensity and carbon performance rating as future performance parameters are introduced. All of the operational needs of the boiler installation are analysed with regard to water flow rate, temperature and pressure, water quality, supply of the common boiler fuels and ventilation requirements. The chapter concludes by discussing the range of standards and recommendations that are potentially applicable to the design of LPHW boiler installations.

Chapter 4 looks at alternatives to the gas and oil-fired boilers of Chapter 3, suitable for LPHW heating applications. Combined heat and power (CHP) is an increasingly popular choice, with its potential economic and environmental advantages over conventional boilers. The relatively high capital cost means that CHP is rarely sized to meet peak heating demand, being used instead in conjunction with conventional boilers. This leads to difficulties in selecting the most appropriate size of CHP and it is hoped that this chapter will shed some light on that, together with how it should be integrated within the heating system. Another increasingly popular system is the heat pump, again offering potential economic and environmental advantages with higher capital costs. The principles of the heat pump cycle are briefly explained, with how it may be used as a source of LPHW and a discussion on the environmental and economic advantages. However, CHP and heat pumps are both large subjects and cannot be dealt with fully here. Finally, alternatives to fossil fuel are discussed. Sustainability is a buzz-word in building services but is yet to make much impact on heating systems. Nevertheless, it is felt that a discussion of the various renewable fuels suitable for LPHW generation should be included in preparation for the changes that are bound to take place in the near future.

Chapter 5 deals with the flueing of boilers. Types of boiler flue are defined, and the nature of *flue draught* is explained. Each type of boiler flue or flue system is then reviewed in turn, including natural-draught and mechanical-draught flues, balanced flues and flue dilution systems. Sizing of a flue or chimney is considered, together with the typical features of its general design and construction. The specific needs of condensing boilers are reviewed, and the chapter closes by noting some acoustic implications for flue design.

Part B looks at the way LPHW systems are designed and operated in order to distribute the heat around the building effectively and efficiently. Chapters 6 to 8 cover emitters, system layout and domestic hot water systems. Chapter 6 deals with room heat emitters including natural and fan convectors, radiators and radiant panels and heated floors. It begins with a review of the types of heat emitter and their construction, giving typical heat output rates. Standard empirical relationships between mean water temperature and heat output are presented, allowing for corrections to manufacturers' data for non-standard conditions. The ratio of radiant to convective heat produced by the emitter has an effect on both thermal comfort and running costs, depending on the thermal properties of the room. This is discussed in detail with examples provided for two very different buildings: a modern office and a factory. The control of emitters is then discussed, looking at variable water flow rate and flow temperature compensation and how they can be usefully combined. The chapter concludes with a discussion of the special case of heated floors which differs substantially from other heat emitters due to the low surface temperature and high thermal mass. Much of the specialist theory used to carry out the analysis, where this is not readily available elsewhere, has been placed in appendices at the end of the chapter to aid fluency of the discussions. Readers may wish to skip some or all of these on a first reading.

Chapter 7 deals with heating circuit design. It begins with a discussion of the importance in choosing appropriate flow and return water temperatures and how this affects many aspects of design. A method of determining the economic thickness of pipework insulation is developed, demonstrating that there may be advantages in exceeding currently recommended thicknesses for environmental reasons at little or no extra cost. Pipework circuit layouts are discussed including variable flow and variable temperature. This leads on to a discussion of pumping methods, particularly using variable speed drives for improved control and reduced running costs. Control valve selection and their performance is covered. Means of allowing for pipework expansion is then examined, together with methods of support and anchoring the forces acting on the pipe. Appendices at the end of the chapter contain the theory used in the analysis of insulation thicknesses, control valves and pumping.

Chapter 8 is dedicated to hot water services. The merits of instantaneous and storage systems are discussed, with methods of determining hot water consumption, instantaneous loads, storage volume and boiler power. The key design aspects of storage systems and hot water generators are discussed. Solar panels, slowly increasing in popularity, are described, together with how the efficiency and output varies with design and weather conditions. (A thermal analysis of a solar panel is provided in an appendix at the end of the chapter.) Finally, the legionella issue, as it applies to the design of heating systems, is discussed.

Chapters 9 to 11 are also analytical in approach and present some (relatively simple) mathematical models to assist in analysing and understanding design decisions. Chapter 9 deals with issues surrounding the installed output capacity of the central boiler plant. It shows the relationship between boiler size and energy consumption in intermittently heated buildings, and uses this to develop a rational method for sizing the central plant. The emphasis is on the designer making decisions based on fundamental principles rather than relying on rules of thumb or tables for which the source of the original data is often uncertain. The principles of intermittent operation are used to explain the operation of optimum start control for switching on the plant, and the chapter concludes by examining the difference between ideal and practical optimum start algorithms.

Chapter 10 looks at the way central boiler plant should be configured and controlled to achieve stable and energy efficient operation. In order to do this it looks at how the configuration of the system can impact on the central plant, in particular how the use of compensator circuits affects temperatures and flow rates around the system. This in turn has ramifications for the way central plant is configured, and the control of boilers will often be dictated by this mix of factors. The importance of temperature sensor location is explained, and boiler modelling is used to show the dynamic effects of different control settings. Guidance is given on how to set up the controls, and mention is made of add-on control devices designed to save energy.

Chapter 11 concentrates on the overall energy performance of a heating system. It presents a modified degree-day approach to energy estimation, and shows how degree-days may be used to monitor a building's energy consumption. The chapter also discusses benchmarking and normalisation of energy use, and discusses ways in which, operationally, a building can be maintained to give maximum performance from the heating system.

Taken as a whole the book should give the reader a deeper understanding of a building services system often taken for granted. Heating installations are so ubiquitous in temperate climates that it is easy to design systems on the basis of what has gone before. This book should explode any myth (if one truly exists) that there is such a thing as a standard heating system, and should strengthen the need for sound design practices. Given that so much of the carbon dioxide emission in Northern Europe comes from heating systems, it is of paramount importance that they are designed and installed to the highest standards that can deliver good indoor environmental quality with the greatest energy efficiency.

References

1. Building Research Energy Conservation Support Unit (BRECSU) (2000) *Energy Use in Offices*. Energy Consumption Guide 19. BRECSU, Garston.
2. Samuelsson-Brown, G. & Whittome, S. (1992) *The Office Sector – A Review of Floor Space, Building Type, Market Potential and Construction Activity in Great Britain*. Report no. MS 7/91, Building Services Research and Information Association, Bracknell.
3. Rickaby, P.A, Bruhns, H.R., Mortimer, N.D., Clark, E. & Steadman, J.P. (1995) *Mechanical Ventilation and Air Conditioning Systems in UK Buildings*, vol. 1–3. Project Report of the Department of the Environment Scoping Study for HVAC Systems. Extracts in *Building Services Journal*, 18, June, 12–13.

PART A
HEAT GENERATION

2 Boilers and Burners

2.1 Definition of a boiler

What is a boiler? Despite the name, the one thing that the boilers serving the vast majority of building heating, ventilation and air conditioning (HVAC) systems are rarely called upon to do these days is to *boil water*. Indeed this is typically the one thing that they must not be allowed to do. The tenth edition of *The Concise Oxford Dictionary* defines a boiler as 'a fuel-burning apparatus for heating water, especially a device providing a domestic hot water supply or serving a central heating system; a tank for generating steam in a steam engine'. This is a basic definition but one that is nonetheless accurate and comprehensive, and the latter part naturally displays the origins of boilers as components of the early steam engines. The definition of a boiler given by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE)[1] is, as one would expect, more detailed and technically specific: 'a cast-iron, steel or copper pressure vessel heat exchanger, designed with and for fuel-burning devices and other equipment to (1) burn fossil fuels (or use electric current) and (2) transfer the released heat to water (in water boilers) or to water and steam (in steam boilers)'.

What then are the essential distinguishing features that enable a 'fuel-burning apparatus for heating water' to function as a practical heating boiler, and to be the kind of heating plant that most HVAC engineers would see as implicit within the ASHRAE definition? First and foremost, it should be capable of heating a continuous supply of water. Second, it should be capable of burning fuel cleanly and efficiently, and in a stable and controlled manner that automatically maintains a specified water temperature within close limits under all operating conditions. This requires a burner and an automatic control system. Finally, the products of the combustion process must be continuously removed and safely dispersed into the general atmosphere, irrespective of the vagaries of wind and weather. This requires the boiler to be associated with a flue or chimney. These defining characteristics of a boiler are illustrated diagrammatically in Figure 2.1. In the following sections of this chapter we will consider boilers in terms of the functional elements that they need to possess in order to achieve the first two of these defining characteristics. The flue or chimney that is necessary to achieve the third is the subject of Chapter 5.

2.2 Principal functional elements of a boiler

2.2.1 Gas-fired boilers

A typical conventional (non-condensing) gas-fired low-pressure hot water (LPHW) heating boiler comprises five principal functional elements:

(1) the boiler 'block'
(2) the burner
(3) the burner gas line
(4) the control system
(5) the boiler casing.

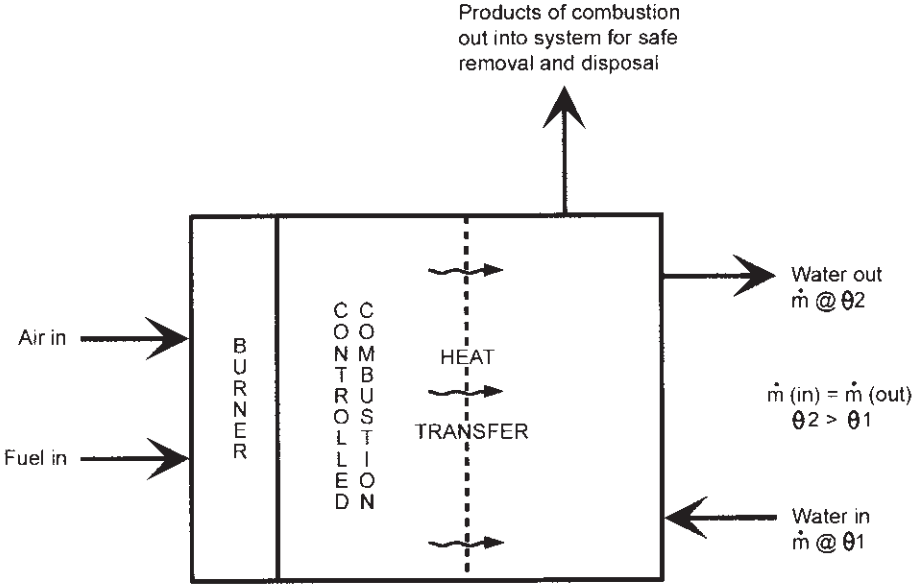

Figure 2.1 Defining characteristics of a boiler.

These are illustrated schematically in Figure 2.2. Each is an assembly of individual components that is more or less complex according to its function. The functions of each of these components, and of the functional elements themselves, are closely linked, and their design and operation must be carefully and thoroughly matched to ensure the safe and efficient performance of the boiler as a whole. Each of the functional elements of Figure 2.2 is considered in more detail in the following sections of this chapter. The point of reference for much of this will inevitably be the conventional *cast-iron sectional boiler* that remains numerically predominant in typical commercial building services heating applications. However, the characteristics of other types of boiler will be considered wherever these differ in principle from this point of reference.

It will make little difference whether the gas on which the boiler in Figure 2.2 is fired is natural gas, manufactured gas (town gas) or liquified petroleum gas (LPG), although within the UK as a whole the choice is effectively between the first and last of these. A complete installation for boilers fired on LPG will differ significantly from one intended for natural gas in its provision of on-site fuel storage.

2.2.2 Oil-fired boilers

In terms of its functional elements a typical oil-fired heating boiler differs little from its gas-fired counterpart. Principally it is more appropriate to consider the burner oil line as part of the fuel supply installation. A complete installation for an oil-fired boiler will again differ significantly from one intended for natural gas in its provision of on-site fuel storage.

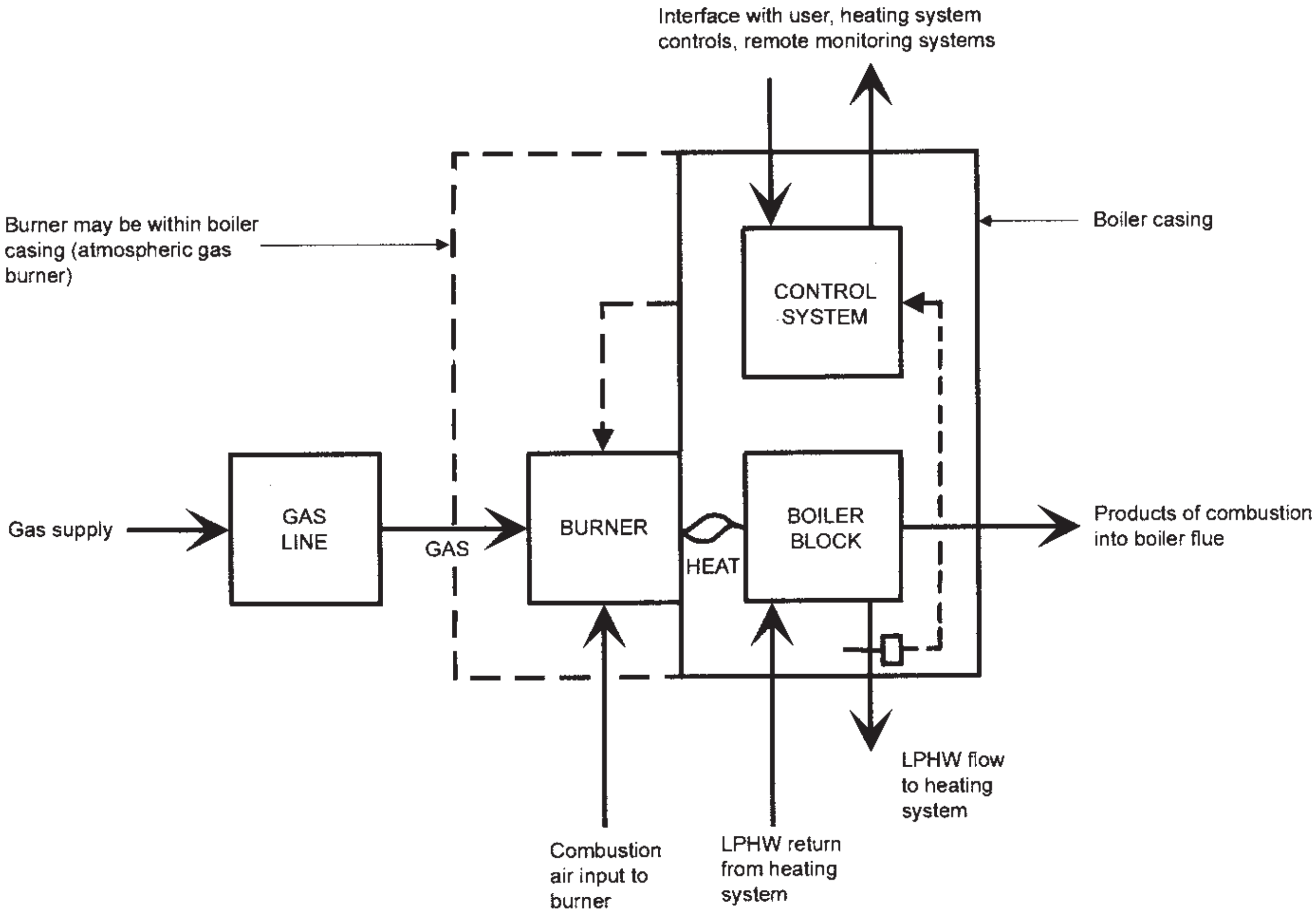

Figure 2.2 Principal functional elements of a gas-fired boiler.

2.2.3 Solid fuel boilers

Within the UK the use of boilers fired on the 'fossil' solid fuels, in particular coal and its related fuel 'family', is now restricted to the large-scale generation of electrical power or to niche domestic applications where alternative fuel sources are unavailable, or simply where it is the *visual attributes* of a fire that are desired. Furthermore, the simple logistics of storing and handling solid fuels make it unlikely that, even should (or when) existing supplies of gas and oil finally run out, there would be a return to widespread coal-firing for commercial or industrial building services applications. Hence for today's HVAC engineers, coal-fired boilers are effectively extinct, and their specific functional requirements and operational and performance characteristics will not be considered in this book.

There is another class of solid fuels for boilers, on which environmental considerations have refocused positive, albeit limited, attention. These are the *renewable* solid fuels, both conventional and new. The former category includes wood derived from forestry operations, the waste products of furniture manufacturing and other woodworking industries, and disposable pallets or other wooden packaging materials. The latter category includes the so-called 'energy crops', of which the most promising appear to be short-rotation willow coppice and miscanthus.

While a building services engineer practising in the UK today may indeed encounter wood-burning in rather specific commercial and industrial heating applications, its scale and technology typically owe more to the stove tradition than to modern boilers. Current thinking regarding energy crops (since there is, as yet, no widespread practice) is directed towards electrical power generation, rather than towards space, air or domestic hot water heating in buildings. Hence boilers or other heating plant capable of firing on the renewable solid fuels will not be considered in this book.

2.3 The boiler block

2.3.1 Function of the boiler block

The boiler 'block' is the primary component of any boiler. It is here that combustion of fuel takes place, and where the high-temperature products of this combustion are brought into sufficient proximity with water from the heating system to allow the transfer of heat from the combustion gases to the water in a controlled manner.

2.3.2 Configuration and design

In order to carry out its function the boiler block contains an area where the combustion process itself may take place. In a cast-iron sectional boiler this typically takes the form of a cylindrical chamber, the *combustion chamber*, which is located either along a horizontal axis in the lower part of the block (Figure 2.3) or along its central axis. In order to transfer the heat generated by the combustion process to water, the boiler block must also contain a network of passages that will allow the hot combustion gases and cooler boiler water to be brought into close proximity, separated only by a relatively thin division formed by the metal of the block itself. These gas and water passages extend throughout the length and depth of the block beyond the

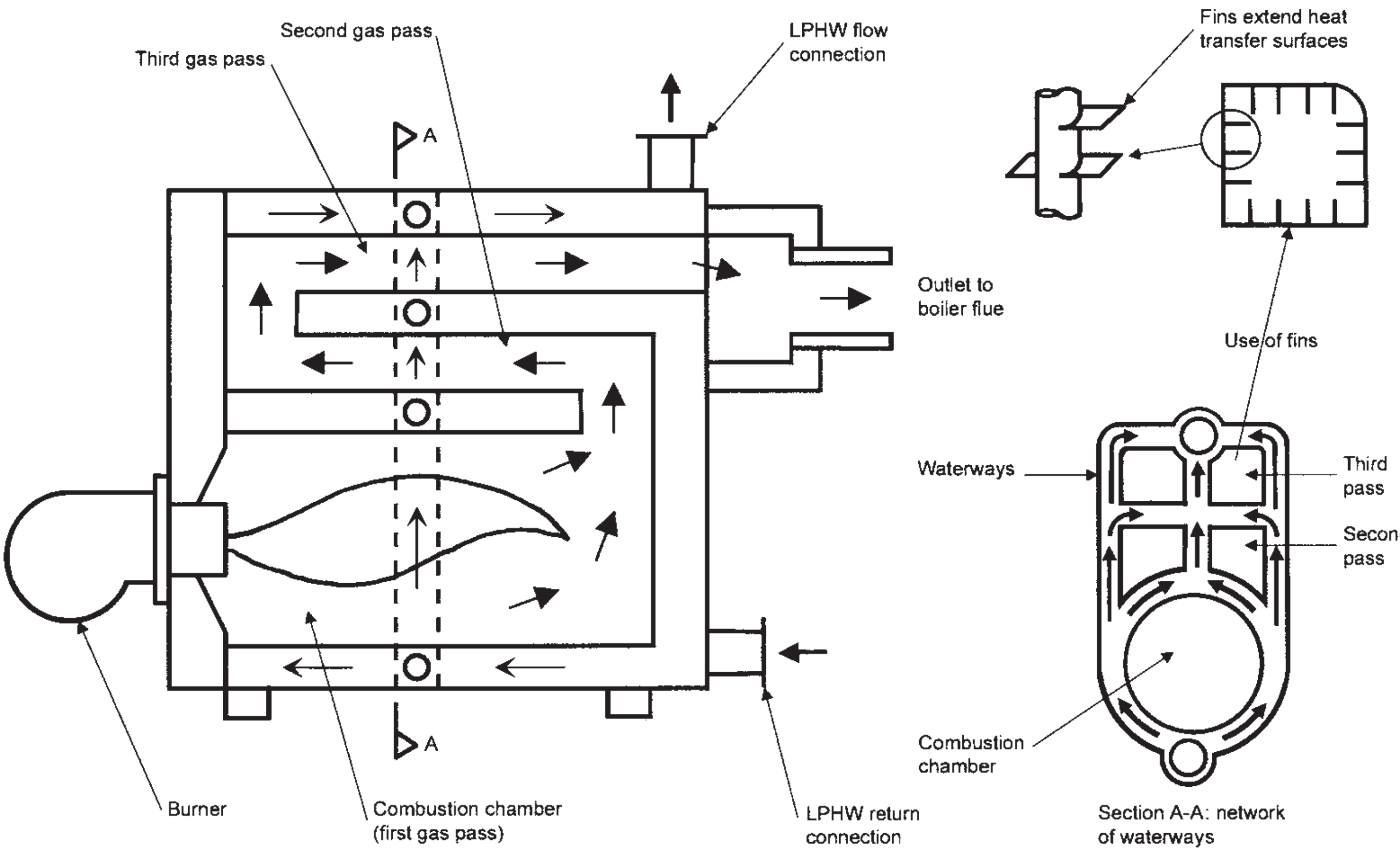

Figure 2.3 The boiler block in a multi-pass sectional LPHW boiler.

combustion chamber. Those passages that carry boiler water are commonly referred to as the *waterways* of the boiler, while those that carry the combustion gases are sometimes referred to as *flueways*. An arrangement of the kind that may be found in many cast-iron sectional boilers is illustrated in Figure 2.3, although the detailed configuration of a boiler block will naturally tend to reflect the specific requirements and characteristics of a particular boiler design. The ways in which types of boiler other than cast-iron sectional differ from the layout shown in Figure 2.3 are outlined in Chapter 3.

The arrangement of vertical waterways shown in Figure 2.3 provides a number of parallel paths for water to flow through the boiler block. It is important therefore that the design of the block ensures that the flow rate of water through each of these parallel paths is matched to the rate of heat input in that part of the block, so that excessive local water or metal temperatures are avoided. The existence of local hot spots, which may result if there are any areas of low water flow rate in the block, can result in local boiling of the water and *thermal overstress* of the metal of the block. Such localised boiling of water in the block is sometimes referred to as ‘kettling’, since its occurrence is accompanied by a noise similar to that made by a domestic kettle at the onset of boiling. Achievement of the correct water distribution throughout the boiler, and the avoidance of short-circuiting close to the boiler flow and return connections, relies on natural balance through attention to the resistance to flow of the various elements that make up the network of waterways. Conversely it is equally important that there should be no areas in the boiler block that are subject to temperatures low enough to cause condensation of the water vapour in the combustion gases. The risk here is that any such ‘cold spots’ will be the site of heavy corrosion that will ultimately lead to failure of the boiler.

The nature of the heat transfer process occurring within the boiler differs between the combustion chamber and the gas passages or flueways. In the former the high temperature of the flame, in which the chemical reactions of the combustion process itself are occurring, generates both radiant and convective heat transfer into the combustion chamber wall that is the primary heating surface of the boiler. The reacting gases themselves generate a low-intensity radiation that is discernible by a faint blue colour. Where particles of unburnt carbon are present suspended in the flame, either as an intermediate stage in the combustion process or as a result of incomplete combustion, they radiate as tiny ‘black bodies’, and their incandescence gives the flame a yellow colour. A flame that is rich in suspended particles of carbon is *luminous*, and radiates intensely. A flame that is relatively poor in suspended carbon particles is *non-luminous*, although it may be appreciably hotter than a luminous one. Natural gas typically burns with a non-luminous ‘bluish’ flame, while fuel oil burns with a luminous flame. In the combustion gas passages or flueways there is no flame, and heat transfer from the combustion gases into the waterways is predominantly convective. The nature of this process involves the operation of complex convective effects on both the gas and water sides of the metal of the boiler block. On the gas side, common practice with heat exchanger design generally employs extended surface areas outside the combustion chamber, and sometimes even within it. In modern boilers these extended heat transfer surfaces are typically achieved by the use of *fins* (inset to Figure 2.3), although thimble-shaped projections or ‘pips’ have also been used. These extended surface areas may also be used to optimise levels of turbulence within the flow of combustion gases, for improved heat transfer performance. On the water side of the boiler metal the transfer of heat depends on the velocity of water flow over the heat transfer surface, which is (as far as the water is concerned) the circumference or perimeter of the waterways. For a given temperature rise of the boiler water higher heat transfer rates typically require higher water velocities. In all modern commercial building services applications water will flow though the boiler as a result of a pumped circulation. However, the velocity of water flow over the heat transfer surfaces of the boiler block will result not only from the effect of the external pumped circulation but also from local convective and 'thermosyphonic' effects within the waterways themselves. Setting up these local convective effects is naturally favoured by a more generous dimensioning of the waterways.

The *water content* of the boiler, i.e. the volume of water that is contained within the boiler block at any instant of time, is naturally a function of the total volume of the waterways within the block. Water content is *independent of the volume flow rate* at which water enters and leaves the boiler via the flow and return connections to the heating system. A low water content produces a more rapid response to changes in the rate of heat input to the boiler, including the important case when firing of the burner commences and heat input changes from zero to the thermal output of the burner. Where the size and/or number of the waterways are greater, the water content of the boiler will be increased. The overall size and cost of the boiler are also likely to be greater. The trend in modern boiler design is towards the achievement of high heat transfer rates in compact designs with low water content, which can provide both a high overall efficiency of conversion between the heat input to the boiler (as fuel) and the heat output from it to water, and rapid response to changes in the rate of heat input. The implications of this for boiler control are considered in Chapter 10.

In order to fulfil its function the boiler block must include two other provisions. First, it must include flow and return pipe connections, so that a continuous supply of water may be received from the building heating system, heated and returned to it. Second, it must collect the 'spent' combustion gases and provide an outlet for them to be discharged into a boiler *flue*, which will ultimately disperse them safely to atmosphere.

2.3.3 The multi-pass principle

Water circulated around the circumference of the combustion chamber provides the first, and primary, stage of heat transfer within the boiler. It is clear that a major aim of boiler design will be to achieve the maximum possible transfer of heat from combustion gases to heating system water for any given rate of combustion of fuel. Since the combustion gases must ultimately be discharged from the boiler and rejected safely to atmosphere, any heat that is not transferred will be wastefully rejected with them. It is also clear that, with plant room space typically at a premium in modern buildings, it is desirable to achieve the maximum heat transfer within a boiler of compact physical dimensions. Modern boilers do not, therefore, rely solely on heat transfer from the combustion chamber. Secondary heat transfer is introduced outside the combustion chamber through the technique of *multiple passing* of the boiler (Figure 2.3). On reaching the end of the combustion chamber, in their first pass along the length of the boiler, the hot gases are typically directed back along the length of the boiler in a *second pass* that takes them through passages that either surround, or are surrounded by, water from the heating system, to achieve additional heat transfer. In the quest for high heat transfer efficiencies, modern boilers have typically introduced further sets of passages that pass the combustion gases back and forth along the length of the boiler a third and even fourth time before discharging them to atmosphere via the boiler flue. Figure 2.3 illustrates a *three-pass* boiler. The configuration of the boiler 'passes', and their relationship to the waterways that distribute water from the heating system through the boiler, is a characteristic of the type and particular design of boiler. At the end of their final pass of the boiler the combustion gases are collected in a manifold or *smoke box* (*smoke hood*), from which they are discharged into a boiler flue. The use of multiple passes produces a complex relationship between the flow of combustion gases and water within the boiler.

The boiler block is thermally insulated to reduce heat loss to its surroundings by convection and radiation from its outer surface. Since the shape of the outer surface of the boiler block may be complex, thermal insulation is typically applied in the form of a flexible blanket. In order to minimise what is, after all, a wasteful loss of some of the energy released by the combustion process, up to 125 mm thickness of thermal insulation may be applied in this way.

2.3.4 Water content and temperature differential

In the UK hydronic ('wet') systems for space and air heating typically employ Low-Pressure Hot Water (LPHW). Boilers are therefore designed with this in mind. The design temperature differential (or rise) of a boiler is the temperature difference through which water from the heating system is raised while passing through the boiler block, with the burner firing at its maximum thermal output. This is a function of both boiler and heating system design considerations. The system design considerations, which relate to the choice of heating system flow and return temperatures, will be examined in Part B of this book. For present purposes it will be sufficient to note that UK practice is typically based on a 'standard' design temperature differential of 11 K across the boiler block, and that this is traditionally assumed to be between nominal flow and return temperatures of 82°C and 71°C respectively. These flow and return temperatures are simple metric conversions from earlier imperial values of 180°F and 160°F respectively (giving a design temperature differential of 20°F). These had been in traditional use in the UK for many years, and there seems little reason to consider that they represent any kind of optimum operating parameters in the context of *either* modern boiler *or* heating system design.

In any event the boiler design temperature differential defines the design flow rate of water from the heating system through the boiler block. For a given heat output to water from the boiler block the water flow rate and temperature differential are, naturally, inversely proportional – halve the former, double the latter. For a conventional (non-condensing) boiler this may be shown by the equation:

$$\dot{Q} = \dot{m}_w c_p (\theta_F - \theta_R) \tag{2.1}$$

where $\dot{Q}$ = heat output rate to water (kW); $\dot{m}_w$ = water mass flow rate ($kg\,s^{-1}$); c_p = specific heat of water ($kJ\,kg^{-1}\,K^{-1}$); θ_F = flow water temperature from the boiler (°C); θ_R = return water temperature to the boiler (°C).

With regard to the temperature range encountered in building services LPHW space and water heating systems and their boilers, it is typically acceptable to regard the density of water as 'fixed' at $1000\,kg\,m^{-3}$ ($1\,kg\,l^{-1}$), so that mass flow rate and volume flow rate are numerically the same.

The minimum water flow rate that will transfer away from the boiler block, under firing conditions, sufficient heat to avoid thermally overstressing it, is typically defined as that resulting in a temperature differential of 20 K, although this may be reduced to as low as 14–15 K for some designs of high-efficiency modular boilers. In the former case the minimum flow rate of water to be maintained through the boiler block under firing conditions would be 55% of that at the design temperature differential of 11 K. In the latter case it would be 70–75%. We have already noted that the volume (and therefore mass) of water contained within the boiler at any instant of time is independent of the rate at which it enters and leaves (and therefore flows through) the boiler. Hence a given mass flow rate in equation 2.1 may be associated with either a high or low water content of the boiler block. Since it is the flow of water through the boiler that carries away or dissipates heat from the boiler block, for a given boiler design temperature differential a high heat output to water inevitably requires a high volume flow rate of water through the block.

Within the boiler, however, we may for simplicity represent the overall heat transfer process by an equation in the form

$$\dot{Q} = UA\Delta\theta \tag{2.2}$$

where $\dot{Q}$ = total heat transfer rate to water (kW); U = an overall heat transfer coefficient for the design of the boiler ($kW\,m^{-2}\,K^{-1}$); A = surface area available for heat transfer (m^2); $\Delta\theta$ = a characteristic temperature difference (K).

Under steady-state conditions, the heat transfer rate in equation 2.2 and the heat output rate to water in equation 2.1 are the same. The *characteristic temperature difference* in equation 2.2 will typically not be the simple difference between boiler flow and return temperatures in equation 2.1, but is more likely to be a *log mean temperature difference* (*LMTD*) based on water and gas-side temperatures. However, neither this nor the origin of the overall heat transfer coefficient need concern us here. What *is* important is to note two things. First, the water content of the boiler block is a function of the value of term A in equation 2.2. This depends on the number and size (typically diameter) of the waterways. The water content of the boiler depends on the *volume* of these same waterways. Second, for a given heat transfer rate and characteristic temperature difference the value of A in equation 2.2 is inversely proportional to that of U. Therefore, with a high value of U the value of A may be reduced for a given heat output to water, and with it the water content of the boiler. When we talk of achieving a high heat transfer rate in a boiler of compact design we are implying that the rate of heat transfer per unit area of heat exchange surface (U) is high, and it is this trend in boiler design that has lead to the typically low water content of many modern boilers. While this is only one aspect of boiler development, it nevertheless has significant implications for the design and control of boiler installations.

2.3.5 Wet-base and dry-base types

In boiler designs where downward heat flow from the combustion chamber is not transferred into waterways, an insulating base will be required to protect the builder's work base or other non-combustible surface on which the boiler is mounted. Designs in which the combustion chamber is surrounded by waterways are defined as 'wet-base' types, those in which the combustion chamber is below the waterways are 'dry-base' types, and those in which waterways wrap around its top and sides (but not below it) are 'wet-leg' types. All three types are illustrated in Figure 2.4.

2.4 The burner

2.4.1 Function of the burner

At the burner the boiler fuel is mixed with combustion air and ignited to produce the flame in which the combustion process takes place. In its simplest form the function of the burner is to safely initiate, maintain and finally terminate the combustion process in response to the requirements of the boiler control system. In the quest for higher seasonal boiler efficiency through improved load matching, the burner may be required not only to maintain the combustion process, but to vary it in a controlled manner according to the demand of the boiler control system.

2.4.2 Boiler fuels and the combustion process

As far as modern boilers are concerned, the common boiler fuels are either gaseous or liquid hydrocarbons. As far as almost all of mainland UK is concerned, the former category typically comprises natural gas or liquified petroleum gas (LPG), while the latter comprises various grades of fuel oil. The 'lightest' grades of fuel oil, 'C' (kerosene) and 'D' ('gas oil'), are those most likely to be employed in modern commercial building services applications. Chemically natural gas and LPG have relatively simple molecular structures. The natural gas supplied for public use in the UK is principally (in excess of 90%) *methane* (CH_4), while the two main types of LPG that are commercially available are *propane* (C_3H_8) and *butane* (C_4H_{10}). The chemical structure of the fuel oils is more complex and may contain various levels of impurities, sulphur typically being that of particular concern in building services applications. In any event complete combustion of the fuel input to the burner is necessary both to obtain the maximum release of energy and to prevent the production of carbon monoxide, which is the poisonous product of the partial combustion of hydrocarbon fuels.

The choice of fuel will be made on the basis of availability, the cost of the fuel itself, the impact of its adoption on the capital cost of the boiler installation and its environmental impact (emission of carbon and pollutants such as oxides of nitrogen and sulphur dioxide). The cost per kWh of heat input to a boiler is broadly comparable for natural gas and the light grades of fuel oil, although absolute costs are typically influenced by annual consumption (consumer purchasing power). On a similar basis the cost of LPG is typically two to three times that of natural gas, which will make it broadly comparable with the cost of 'off-peak' electricity. While for identical heat outputs the capital cost of oil-fired commercial space and water heating boilers is