



COMBUSTOR CHARACTERISTICS

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COMBUSTOR CHARACTERISTICS

A combustor is the equipment where combustion takes place, usually a combustion chamber, and it can be a complex system that is best studied by considering its main parts and processes separately. The different types of combustors were reviewed in [Combustion characteristics](#); we here intend to give a general idea of the basic parts of all combustors.

The analysis of a combustor may be, in order of increasing generality:

- Specific combustor types: steady and unsteady combustion chambers, and practical burners.
- Generic combustor subsystems and processes: intake, injectors, igniters, energy flows, exhaust, safety and controls.
- Basic combustion processes: combustion at rest, non-premixed flame, premixed flame (deflagration wave, detonation), pollutant generation.
- Fundamentals: Chemistry (in particular Chemical Kinetics), Thermodynamics (in particular Chemical Thermodynamics), Heat and Mass Transfer, Fluid Mechanics (in particular gas flow and turbulence)...
- Ancillary sciences (needed for the modelling and validation of theories and practical design): Mathematics (analytical and numerical modelling) and experimentation (test rig preparation, instrumentation, data acquisition and analysis).

The practical goal in the analysis of combustion devices is the prediction of its performance (for present and future combustors), in terms of the multiple physico-chemical phenomena involved; it is thence a prerequisite to analysis the latter.

We try to focus here on combustion basics, i.e. consider a generic combustion system as used in applications (Fig. 1), but analyse mainly its fundamentals. The objective is to understand the influence of

the main parameters in combustion, in terms of predictive models (not just descriptions of particular cases).

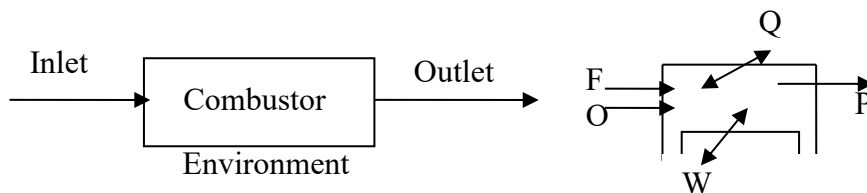


Fig. 1. a) Generic steady-state combustion chamber and its interactions. b) unsteady chamber in reciprocating engines (F: fuel, O: oxidiser, P: products, Q: heat, W: work).

It is good to always keep in mind the steady-state combustor with one inlet and one outlet (a simple control volume approach), and consider other cases as variations of this simple scheme: the enclosure may be imaginary as in a simple candle flame, the inlet duct may be actually split in two (one for the fuel and another one for the oxidiser), there may be neither inlet nor outlet (in reciprocating engines with valves closed), the outlet may (theoretically) be considered split in as many ducts as chemical species are (to provide a common thermochemical reference to each species), etc.

Inlet flow (intake)

What to study:

- **Fuels.** Types, availability, price, convenience (better if fluids), additives (water, octane index promoters, lubricants, stabilisers). A detailed description of fuels can be found in [Fuels.pdf](#).
- **Oxidisers.** Types: ambient air is the most used because it is free, but preheated air, enriched air (up to pure oxygen), depleted air (mixed with exhaust recirculation), and other oxidisers (as for rocket propulsion) may be used.
- **Mixture ratio specification.** There are several ways to specify the mixture ratio: fuel molar-fraction in the mixture, x_F ; fuel mass-fraction, y_F ; fuel/air ratio (molar or mass), f ; air/fuel ratio (molar or mass), A ; air ratio (to stoichiometric air for constant fuel flow; also known as aeration or simply 'lambda'; it is the same in molar and mass basis), $\lambda = A/A_0$; equivalence ratio (the fuel/air ratio relative to stoichiometry; it is the same in molar and mass basis), $\phi = 1/\lambda$; excess air, $e = \lambda - 1$; mixture (mass-flow-rate) fraction, etc. (Note that sometimes λ is named excess air ratio or even excess air, instead of air ratio). Most industrial burners and SI-engines use near stoichiometric mixtures, whereas CI-engines and gas turbines use very lean mixtures. SI-engines using three-way after-burning catalysers must use stoichiometric mixtures ($\lambda = 1$) for proper operation, but homogeneous-charge SI-engines may work up to $\lambda < 1.6$, a range that is extended in stratified-charge SI-engines (direct gasoline injection may work up to $\lambda < 3$, and direct natural-gas injection up to $\lambda < 10$ of overall mixture ratio).
- **Mixture preparation.** It depends on the type of combustion wanted: premixed, or non-premixed. Fuel and oxidiser must be pumped for normal pressurised combustion (they are aspirated in depression combustors). Liquid fuels must be quickly vaporised within the oxidiser (only vapours burn). The liquid fuel may be supplied at high pressure into the combustion chamber in order to quickly form a burning spray, or vaporised into the oxidiser stream, either far upstream in the carburettor of a classical premixed-combustion engines, or at the intake manifold as in most

current Otto engines, or within the cylinders (direct injection). In Otto engines, indirect fuel injection at the manifold may be at 300..400 kPa, whereas direct injection in the cylinder at the end of the compression phase may be at 3..10 MPa for direct injection spark ignition Otto-engines (DISI) and 30..200 MPa for direct injection compression ignition Diesel-engines (DICI). Most modern injection systems are electronically controlled. Lean pre-vaporised premixed combustion (LPP) is under study to reduce the temperature and NO_x emissions in gas turbines. For coal chunks and other solid fuels burning over a grate, the best in mixture preparation is to split the air intake in two streams, one for under-fire air, and the other for over-fire air.

Chemical notation (particularly hydrocarbon chemistry) and stoichiometry (the proportions in which atoms are combined in molecules) must be considered, and distinction made between stoichiometric equations (e.g. $C+O_2=CO_2$ or $C+(1/2)O_2=CO$) and actual mixture equations (e.g. $C+aO_2=bCO+cCO_2+dO_2$ or $aC_uH_vO_wN_xS_y+aA(c_{21}O_2+c_{79}N_2)+cH_2O+dO_2=\sum(x_iM_i)$), depending on the choice of unit-fuel-amount or unit-exhaust-amount of substance, for a given oxidiser/fuel ratio, a in the first instance or A in the second. Actual mixing, by non-premixed feeding, convection, evaporation and so on, may be considered also here (e.g. for spark engines: carburetion, intake-port injection or direct-cylinder injection).

DUAL FUEL COMBUSTORS

Combustors have been traditionally classified according to the type of fuel they were designed for, and for their size, of course. For instance, a gasoline spark-ignition engine cannot be fed with any other fuel; really, some amount of a compatible fuel may be added, as when up to 20% bio-ethanol is added to normal gasoline. And similarly for a kerosene-fuelled gas turbine or any other internal combustion application. Of course, external combustion applications, like a boiler and some type of furnaces, may run with heat produced by the combustion of any kind of fuel, but the hearth where the combustion takes place is also fuel-specific, within small variations.

But there has always been a push to provide a dual-fuel capability, initially to be able to burn new fuels in old systems (coal in wood grates, oil in coal hearths, natural gas in oil burners, etc.), later to cope with fuel restrictions (gasogens during the wars), and nowadays to limit pollutant emissions (e.g. city fleets of taxis and buses on LPG and NG, clean diesel oil for port and coastal operations of ships, and cheap dirty fuel-oil for deep-sea operation, etc.). We do not consider under the dual-fuel heading the capability to use a fuel and electricity (as a second energy source).

Dual fuel combustors can switch to a different fuel by just manually or automatically turning a control valve; of course, any combustor prepared for any fuel might be fully modified to run on any other fuel, but this is of little interest, except when an existing combustor is to be definitively transformed, as when a fleet of city buses is transformed from diesel-oil to natural gas (to reduce pollution) and the modified engines cannot work with diesel-oil any more.

The common dual-fuel systems in use are:

- Otto dual-fuel engines, where a gasoline engine system is modified to run also on propane (LPG really) or methane (really compressed natural gas CNG typically at 20 MPa, or liquefied natural gas LNG from a cryogenic reservoir). The changes required are: the additional fuel tank (to be refilled in situ or exchanged and refilled off-line), the fuel lock valve, a liquid-to-vapour converter (if any), a gas mixer or a gas injector device, and the switching valve for the driver (most times an additional fuel storage meter is added). The engine itself is not modified, or very little, since the combustion process is similar or even better (e.g. LPG and NG have larger octane-number than gasolines). Otto dual-fuel engines switch from one fuel to the other by a simple feeding switch, manually or automatically operated.
- Diesel dual-fuel engines, where a diesel engine system is modified to run also on CNG or LNG. The problem here is that the high-pressure gas-fuel-injection would consume a lot of power (some 30% of the heating value of the gas), what might be reduced by compressing LNG if available, or, for most practical systems, by feeding the gas at the modified intake manifold and using some diesel oil in the normal way to ignite the mixture (always), and (in most cases) to complement the required fuel load (up to 20% diesel oil plus more than 80% natural gas is the common approach). Dual fuel diesels presently run only in the 4-stroke mode. Notice that sometimes the term dual-fuel diesel engine refers to the capability to run on light and heavy fuel oils. Notice also that most diesel-oil engines would run on biodiesel with none or minimal change, and even on straight vegetable oil with some modifications. A control electronic unit is required to adjust the dual-fuel supply, and some liquid fuel is always required to quickly ignite the mixture at each cycle (engine start-up is done with 100% diesel oil).
- Brayton dual-fuel engines, i.e. gas turbines running on kerosene or natural gas. Most dual-fuel systems work in the normal non-premixed mode, but some lean premixed combustion systems (vaporising the liquid fuel before combustion) are also been developed.

External combustion applications running on dual fuel are basically a dual burner within the same combustor. A typical dual-fuel external-combustion applications is the steam turbine in a classical LNG carrier ship, where the natural-gas boil-off is burnt in the boilers, besides the normal heavy-fuel oil.

Internal flow

Internal flow field depends a lot on the type of combustor. In modern combustors, recirculation of exhaust gases (EGR) is a common practice. In all practical cases, the internal flow is highly turbulent, and many times with forced swirling at the injectors. Typical mean flow velocity inside combustion chambers of gas turbines are in the range 15..25 m/s for industrial gas turbines and 25..50 m/s for aeronautical turbines.

Outlet flow (exhaust)

What to study here: types of exhausts conditions according to heat transfer (from isothermal to adiabatic), exhaust gas composition (complete-oxidation model, chemical-equilibrium model with $\prod(x_i p/p_0)^{v_i} = \exp(K(T, p_0))$, possible condensation, emission of contaminants) and exhaust temperature.

Environmental effects are usually identified with pollutant emission through the tail-pipe because this is the major source, but there are others (see below). The use of exhaust scrubbers and exhaust catalysts are

crucial for pollutant control. Emissions from cars, the major pollution source in cities, have realised a unitary reduction (per car) of 50% from 1970 to 1990, and a drastic reduction around 1992 (another 40% from 1990 to 2000). A detailed description of pollutant emissions and fire safety can be found in [Environmental effects and hazards in combustion.pdf](#).

Closely related to the exhaust ducting is the chimney, the vertical part of the exhaust piping intended to create a natural draught and a far disposal of pollutant emissions, used in stationary and large mobile combustors.

Heat and work flow

What to study: energy balance for the combustor: $dE=dQ+dW+\sum H_i^*dn_i$, amount of heat transfer (from zero to the calorific value), amount of work transfer (from zero to the maximum value: the exergy of reaction). Heat transfer mechanisms in combustion, the main one being convection but radiation effects sometimes crucial. Heat sinks in combustion: walls, heat exchangers, heating of a furnace load. Combustor walls usually have to withstand high temperatures, like within furnaces, and thence an inner lining of refractory material (fire bricks or monolithic) is applied.

Notice that heat and work are path variables, being different for constant-volume combustion than for constant-pressure combustion, for the same fuel/oxidiser mixture. Furthermore, it is sometimes wrongly assumed that a given chemical reaction always gives more heat than work; it might yield even more work than the maximum heating value, as for instance with $C+O_2=CO_2$, that has a maximum heat potential at standard conditions of 393.6 kJ/mol ($-h_r^\oplus$) and a maximum work potential of 394.5 kJ/mol ($-g_r^\oplus$).

POWER INTENSITY

As for other engineering processes, the main interest is not on integral heat and work, but on heat and work flow-rates, i.e., on combustion intensity, either per volume of combustor (in kW/m³), or per cross-sectional area perpendicular to the main flow in the combustor (in kW/m²). Combustion intensity is the product of mean reaction rate times fuel heating value; to increase the former, the area being burnt must be increased (e.g. by turbulence), the temperature must be increased (e.g. inside a porous matrix burner), or a catalyst must be used (catalytic combustion may be used to stabilise low temperature flames instead of increasing their intensity).

EFFICIENCY

Different kinds of efficiencies can be defined:

- System efficiency. It is usually defined as the ratio of useful energy extracted from the system (a boiler, an engine) to the available heating value of the fuel supplied (care must be paid to find if the HHV or the LHV has been chosen). Typical values are 90% for a boiler and 40% for an engine; the rest of the heating potential goes as enthalpy of exhaust gases, or as heat losses to the environment through the walls. These are just energy ratios that do not take into account thermodynamic limits, an exergy ratio being sounder (the exergy extracted, per unit of fuel exergy input, is some 30% for a boiler and 40% for an engine).

- Combustion efficiency. It is usually defined as the ratio of actual heat released with intake at standard conditions and exhaust transported to standard conditions at constant composition, to the maximum heating value of the fuel (roughly the HHV); typical values in well-operated combustors is >98%. Real combustion processes do not yield their maximum heating value because of unburnt emissions (soot, CO, volatile organic compounds) and condensables. Combustion efficiency in hydrocarbons practically coincides with the carbon conversion fraction from fuel to CO₂, since hydrogen oxidises more readily, but nitrogen oxides may be present too. Sometimes, a boiler efficiency is called combustion efficiency, but the numerical values usually clarify the distinction.
- Combustion efficiency in 'adiabatic combustors'. In a fixed wall (i.e. without work exchange) combustion chamber intended to be adiabatic (like in a gas-turbine combustor; i.e. without a secondary on-purpose heat-extracting fluid), combustion efficiency is defined as the fraction of the LHV that exits as thermal enthalpy (sensible and latent) of the exhaust stream, with the 'lost fractions' being the residual chemical energy of unburned components in the exhaust, and the heat losses through the wall. Notice that this definition corresponds to a system efficiency if one considers the combustion gases themselves as the energy-extracting medium (like the heated water in a boiler).

In any case, the usual assumption in most combustors is that the heat lost through the external combustor walls is negligible against the enthalpy flows involved.

POWER MODULATION

Combustors are usually optimised to work at a nominal load, but are usually required to work at different loads. Non-premixed flames are stable in a very wide range of flow rates, and thus of power, but the more-powerful normal premixed flame gets unstable below 50% of full load (flash-back extinction occurs, and blow-off extinction in the upper limit). Outside of this flame-stability range, either a non-premixed flame is allowed (with size increase, and CO and NO_x increase), or some burners must be switched off (causing uneven temperatures and start-stop increased emissions), or new porous combustors developed...

For instance, consider the case of home boilers. They usually provide space heating and hot water. Hot water (in line) requires a minimum of 15 kW for small periods (less than 15 minutes), whereas a 100..150 m², 4-person family home in mid-latitudes may require from 2..15 kW of heating, depending on wall insulation and external temperature. The normal premixed flow, the one used in traditional water heaters, yields an unstable flame below 50% of full load, thus current home boilers may be modulated between 7..15 kW (heating is temporarily stopped when hot water is needed), matching the demand by an on/off control that increases pollutant emissions at every start. On the other hand, for better comfort on hot water demands, i.e. if more than 15 kW were needed (e.g. two showers at a time), if intermittent user-demands (e.g. at the sink tap) are to be smoothed, and if startup-times of the boiler are to be skipped, the best is to provide a hot-water storage tank of some 50..100 litres, at the expense of its continuous heat loss.

Combustor internals

What to study: description of types of burners (see Combustor types), types of flames, mechanisms for ignition, stabilization and extinction; and analytical models for internal processes and kinetics (flow and chemistry), to evaluate the combustion rates and required sizes and times. Chemical kinetics and physical transport processes may become too complex if the flow field is not drastically simplified. Sometimes measurement and control systems are here considered (e.g. flame detectors), but instrumentation is also applied to the intake to regulate the flow and to the exhaust to monitor emissions.

TYPE OF FLAMES

According to the type of flame, combustion processes may be grouped as:

- Non-flame combustion. Usually identified with low-temperature catalytic combustion.
- Non-visible-flame combustion. Usually identified with porous media combustion, although there are also nearly-invisible flames, as premixed hydrogen/air or methanol/air...
- Non-premixed combustion, usually divided in:
 - Homogeneous combustion of gaseous fuels, as a butane jet in air.
 - Homogeneous combustion of condensed fuels, as gasoline vapours in air.
 - Heterogeneous combustion of condensed fuels, as for coal burning and solid charring.
- Premixed combustion, usually divided in:
 - Unsteady process: ignition (local or global light-off), extinction (effect of air/fuel ratio, quenching).
 - Steady process: deflagration speed, anchored and travelling flames.

Chemical kinetics is perhaps the hardest theme to study, due to the intricate mathematical models (very stiff problems because of the widely different orders of magnitude involved) and the scarcity of reliable experimental data. Topics to be studied include: speed of chemical reactions, law of mass action, elementary reaction mechanism, first-, second- and third-order reactions, partial-, steady- and frozen-equilibrium reactions, initiation-, propagation-, branching- and termination-reactions, Arrhenius law, etc.

TYPE OF GEOMETRY

Concerning the geometry of the combustion process, the traditional division in combustor modelling is:

- Uniform combustion model, as for still-reactors and well-stirred reactors.
- One-dimensional combustion models, as for plug-flow reactors and spherical combustion.
- Two-dimensional combustion models, as for planar and axial jets.
- Three-dimensional combustion models, basically generic CFD codes.

We have focused here only on the characterisation of combustors from the combustion point-of-view, not considering other important aspects of combustors as their construction, operation and maintenance details, which depend a lot on the particular application envisaged: furnace, boiler, turbine, etc.

For instance, in jet-engine combustor, an outer case holds the pressurised gases against the low external ambient pressure, and an inner perforated liner holds the hot burning gases while providing primary air sustain the flame, and secondary air to dilute the burnt gases and lower the temperature some 500 K

before entry to the turbine; in spite of being cooled by secondary air on both sides, special thermal-resistance alloys are still required for the liner. Fuel is injected behind the leeward dome of the liner through a swirler to accelerate mixing (liquid fuel gets atomised, and air flow gets more turbulent; however, the higher the turbulence, the higher the pressure loss in the combustor).

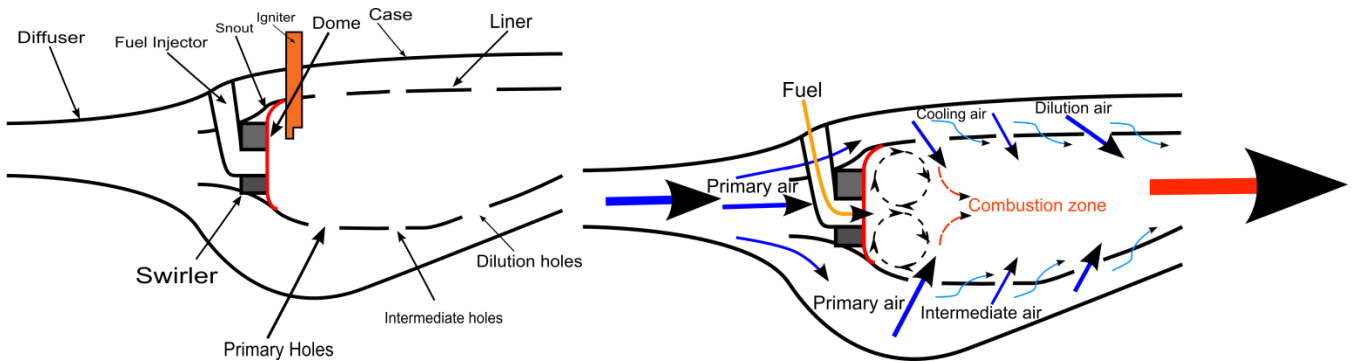


Fig. 2. Diagrams of components and flow paths in a gas turbine combustor (from [Wikipedia](#)).

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