

## **Catalytic Combustion for the Gas Turbine a Review of Research at Cranfield University**

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### **Abstract**

Catalytic combustion is the cleanest emissions technology that has been demonstrated for the gas turbine. It has been a primary part of the research portfolio for the Combustor and Heat Transfer Technology Group at Cranfield University since 1989. The Paper describes the background to studies in the Group, their evolution and presents some results for specific study areas and themes.

### **Introduction**

The Combustor and Heat Transfer Technology Group concentrates on low emissions applied combustion research, especially for the gas turbine. The Group has operated in this area for 30 years and draws on a broad background of associated studies that have been a feature of Cranfield since its formation in 1946. Much of the Group's work has been on suspended turbulent flame combustors for aero and industrial gas turbines but also includes specialised industrial process and general applications.

Cranfield was formed as a post-graduate School originally to serve the aero and aero derivative industries. As such, it has a long history of gas turbine research, covering systems, cycles and component technology. For a University, Cranfield has large and well-found experimental facilities that enable gas turbine full-scale conditions to be represented to approximately 20 pressure ratio (simple open cycle) and, separately, flows to Mach 2 at 1800K stagnation temperature. These facilities were recently refurbished with the aid of a Government Grant and have been extended in flow capacity to approximately 4.3 kg/s. Table 1 gives some leading particulars for the experimental capability.

The predominant fuel for industrial gas turbines remains natural gas, although pressure on carbon emission has renewed interest in fuels from biomass and coal. In addition, waste streams such as sludge, farm residues and municipal waste are being seen as continuous fuel feedstocks that may provide useful power, reduced emissions and deal with a difficult disposal problem at a local level [1 – 3]. Schemes using Distributed Generation (DG) and CCHP (Combined Cooling, Heat & Power) usually involve electrical powers from 50kW to 1MW, whereas larger IGCC and CCGT plants run from 5MW to 200MW for IGCC and 100MW to 600MW for CCGT.

With increasing emphasis on pollutant emission during the 1970s and 1980s, a research strand was sought in the Group that represented ultra-low, fuel-flexible combustion technology. The technique of catalytic combustion for primary energy conversion that appeared in the mid 1970s posed significant

research challenges, initially mostly in the chemistry, formulation and production of catalysts. The Group was approached at that time to collaborate with a major catalyst manufacturer but for resource reasons the initiative did not continue. When, in the mid 1980s, the opportunity was favourable and we were already working on privately funded catalytic combustion research for a major company, a large UK Government-supported Programme was proposed and secured in conjunction with two companies and one other university research group. In cases where Cranfield has no appropriate skills or insufficient technical depth we prefer to develop partnerships with others, thereby extending the best points of the project team. The LINK catalytic combustion project was a case in point and represented a large investment by all the project parties. Since then, a number of similar initiatives have been followed, not only in catalytic combustion but also in turbulent flame combustion work. Table 1 sets out some other significant milestones in that process, since 1990. Continuing research projects supported by industry and agencies form the greater part of the Group's activities: many are collaborative and currently research links exist with France, Italy, Japan, Russia, Sweden, Switzerland and North America. In addition, over the same period, a variety of MSc, PhD and Intern students, plus short term post-doctoral researchers have studied in the Group from several countries: Canada (2); France (2); Holland (1); Sri Lanka (1); Cyprus (1); China (1); Turkey (1); UK (3); USA (4). Together with the research staff that form the basis of the Group, these personnel have enabled curiosity-driven research to be undertaken, associated with the larger, applied science programmes. These studies add appreciably to the Group's knowledge base. The Group's emphasis is on the translation of engineering science to practical devices, so it creates and draws on a wide spectrum of information. In nearly all areas there are gaps in basic engineering science data. With this in mind, individual studies will be formulated in large projects to supply additional material, or appropriate research proposals and presentations submitted to fill gaps. These are often the subject of student or post-doctoral participation.

In the case of catalytic combustion for the gas turbine, many of the original problems faced in the early years still exist but at different levels. The need now is as much to collect this data together in a unified systematic fashion to permit direct application to particular engines, cycles, fuels and systems, as it is to deepen some of the knowledge. Some of the areas we have studied with a view to building this level of system expertise and competence are described below.

#### **1. Catalytic Combustor Performance and Emissions**

The three main variants of catalytic combustor have been studied in the Group for gas turbine applications and are shown schematically in Figure 1. Our studies have been on generic combustor geometries, using natural gas and synthetic synthesis gases simulating a number of precursor processes. The combustors have been operated over representative conditions up to an engine pressure ratio of 16, with correct air and fuel mass loadings, air preheat and combustor air:fuel ratio. Figure 2 shows the generic combustor that has been used for simple and catalytically-stabilised work, which can have a multi-monolith arrangement with gas sampling between monolith stages, plus internal monolith temperature measurement using thermocouples, and exhaust gas temperature and composition measurement. Two pressure casings are available, with diameters of 250 and 406mm, giving maximum monolith diameters of 150mm and 200mm. Our work has concentrated on two main areas, emission control and performance

envelope, with data obtained at representative cycle conditions.

### **Thermal Nitrogen Oxides' Control**

A large database of performance characteristics at combustor pressures to 16atm, combustor inlet temperatures to 740K (unvitiated) and 850K (vitiated) and combustor exit temperatures to 1700K has been gathered, for natural gas. Some of this work used the partial catalytic or catalytically supported combustion regime, with homogeneous phase combustion to complete the reaction and avoid over-temperature to the final catalyst stage. With natural gas, very low values of pollutant emission have been measured, comparable to those noted elsewhere in the literature [e.g. 4, 5], typically  $\text{NO}_x < 10$  ppm;  $\text{CO} < 10$  ppm;  $\text{UHC} < 5$  ppm at oxygen levels between about 12 & 19%. The data set covers inlet velocities from 10 to 40m/s, air:fuel ratios from 45 to 300, vitiated and unvitiated feeds [6]. In addition to the direct measurement of performance parameters, effects of air:fuel mixedness have been assessed: this is an important area for the catalytic combustor, as it is for the lean premixed (and pre-vaporized) flame combustor, especially with fuels having low spontaneous ignition temperatures and low ignition energies. It was shown that efficient catalytic combustion of natural gas could be achieved at inlet velocities up to about 30m/s for the catalysts of the day, with combustor pressure losses below 3% for a single monolith and operating pressures to 16atm. A means of raising the mixture temperature above the polytropic compression value for the cycle pressure ratio was required however, to sustain consistent performance with the catalysts used.

The effects of using a pre-burner to initiate the combustion reaction can be marked, with higher CO and UHC produced due to the depressed catalyst activity resulting from saturation of active catalyst sites by water and carbon dioxide from the preburner. Much of this data relates to privately-supported research. The use of multiple monoliths in series flow raises the system pressure loss appreciably and is one of the limitations of the fully catalytic combustor for high exit temperatures. Values up to ~10% of the total pressure may be expected for the entire combustion system gas path, including preburner, fuel injection and monolith system for inlet flow Mach Numbers ~0.075, [6]. In addition to the beneficial, well-known emissions performance of catalytic combustors, another advantage is that they are low acoustic-emission devices and this has been proven by pressure transducer data from the full-density experiments.

The experimental work was supported by numerical modelling and detailed studies of single channel flow obtained from super-scale models, set out below.

### **Fuel-bound Nitrogen Conversion**

Extension to synthesis fuels derived using precursor techniques such as digestion, gasification or pyrolysis introduces another important study area: control of Fuel Bound Nitrogen conversion to nitrogen oxides. While the thermal control of  $\text{NO}_x$  by catalytic combustion (and other means) is well and consistently demonstrated, the FBN problem limits wider exploitation of renewable and waste-derived fuels, which could provide a significant benefit in global carbon dioxide control and a valuable interim phase to the ideal of a near zero carbon economy, whilst providing a clean disposal route for many

materials. The only suspended flame technology to have shown reasonable performance with high FBN fuels is rich-lean stoichiometry control [7] and it cannot presently attain the widely legislated limits operated world-wide.

Small-scale power generation from a variety of fuels such as biomass, oil residues and wastes has special attractions in energy economics and security of supply. In particular, the utilisation of biomass as an energy source for thermal power generation in Integrated Gasification Combined Cycles has drawn special interest for power generation in the 5 to 30MWe range [e.g.1]. Local or distributed generation (DG) can make a contribution to the domestic, residential and light industrial sectors and contribute to the grid in deregulated supply economies, or it may be a sole source where there is no grid connection. Distributed Generation is often limited by legislation to power deliveries to the grid greater than about 500kW, which is a size at which small gas turbines without auxiliary heat recovery are attractive. Lower power gas turbines of, say 50kW and above with exhaust heat recuperation, contribute efficiently in Combined Cooling, Heat & Power schemes where the intrinsically poorer cycle efficiency of the gas turbine is offset by low fuel consumption. Other, fuel-flexible, prime movers include Stirling engines and Reciprocating Gas Engines, all fitting into the 5 - 500kWe power range. The Stirling engine is also a candidate for a catalytic combustor.

In most cases the precursor processes involved in the production of synthesis gas produce fuels of low calorific value, therefore more of the fuel has to be injected into the engine to produce the net power output. Many of the trace contaminants can be retained in the conversion process from raw fuel to syngas, but the biogenic nitrogen content appears in the fuel as ammonia and/or other nitrogenous compounds, e.g. HCN. The conventional method of cleaning by water washing introduces a large enthalpy loss to the cycle and this significantly and adversely affects plant economics. If the ammonia and nitrogenous species can be treated in the gas turbine combustor without losing their intrinsic enthalpy from the feed process, substantial benefits are possible. This was the target of our project in the first UK Government's Foresight Challenge competition, Table 2 and [8], which resulted in a programme that studied both the catalysts and the processes involved. We have used selective catalytic reduction to reduce ammonia contents in synthesis gases by quite large amounts. The activity has continued as internally funded research at Cranfield since the closure of the main programme and some results have been presented [9, 10, 11]. Two reactor schemes have been studied, the first taken from microreactor catalyst screening trials in the Foresight Challenge project [9]. The microreactor study used gases with low CO/H<sub>2</sub> ratios and achieved conversions above 90% of ammonia to nitrogen with the most promising formulation, 2% Rh/Al<sub>2</sub>O<sub>3</sub>. This was translated to a 30mm diameter, 50mm long cordierite monolith having 400 cells per inch and a 22% La washcoat, for high pressure evaluation, Figures 3 and 4. In this form, conversions up to about 40% of ammonia to nitrogen only were obtained at high space velocities and operating pressures, with representative fuel gas compositions although the data published is not for an optimised reactor. The process is affected by the CO/H<sub>2</sub> ratio in the fuel gas, having a clear operating temperature window, Figure 5. Subsequent work [11] with a two-component reactor, aimed at a fuel treatment process for micro gas turbines, yielded better conversions. There are two possible dry NH<sub>3</sub>

destruction reactions

Thermal decomposition



Oxidation



The fuel composition and conversion data is given in Tables 3 and 4. The results relate to the heterogeneous catalytic conversion of  $\text{NH}_3$  to  $\text{N}_2$  at a gas-solid interface using a monolith catalyst under a controlled oxygen atmosphere. The catalysts investigated were supported  $\text{Rh}/\text{Al}_2\text{O}_3$ ,  $\text{Pt}/\text{Rh}/\text{Al}_2\text{O}_3$ , and  $\text{Pt}/\text{Pd}/\text{SnO}_2$ , operated with a synthetic fuel gas blended from seven individual streams to make up the desired composition, Figure 3. The reaction is sensitive to temperature, and  $\text{NH}_3$  conversions of up to 90% have been achieved, without additional reactor tailoring. The temperature of the catalyst bed is maintained by finely controlling a small amount of oxygen, fed as air. The catalyst substrate is cordierite honeycomb with square cells. The dimensions of the catalyst monoliths were 30 mm in diameter and 50 mm long with 400 cells per square inch.

## 2. Numerical Models

Zone, lumped parameter, and CFD-coupled chemistry models have been examined. The zone models use performance measurements from the simple and CSTC-geometry experiments to develop one-dimensional (zero radial heat loss) models based on the heat and mass transfer analogy and so assume mass transfer limited processes with simple, fast, chemistry. Measurements on multi-monolith reactors operating on natural gas showed that the fuel's combustible components were consumed at sensibly equal rates in each stage of the monolith assembly, at least to about 1000K: thereafter this remained a good first approximation. This suggests that a global kinetic scheme can be employed for initial performance estimation, on a stage-by-stage basis. The global reaction equation is different between stages because of the variation in mass transfer control and the effect of homogeneous reactions. Such models are useful for preliminary sizing but they are limited by several things, including channel aspect ratio and operating Reynolds Number. Measurements of monolith internal temperature show that long monoliths operate at quasi-uniform heat flux over roughly the middle portion of the monolith. At the ends, altered heat transfer rates violate the assumption of uniform heat flux. The heat flux variations may arise from several sources; increased mass and heat transfer in the inlet section of the channel and radiation losses from the hot channel ends being the principal ones. In some cases, these effects broadly cancel, leaving the lumped parameter model as a fair initial estimate for non-specific reactions of similar rate, such as might be represented by complete oxidation of methane-based fuels. The treatment of radiation in zone models is important as it is the dominant mode of energy transfer at high temperatures. Considerable effort has been expended to make such models fit experimental observation by refining their content [e.g. 12]. Our study of zone models for natural gas combustion gave a reasonable fit to experimental data and permitted prediction of performance at other operating conditions but suffered lack of detail. It also only provided a vehicle for prediction of  $\text{NO}_x$  from a temperature-related Zeldovich

correlation, which was insufficient for the accuracies sought. These conclusions led to a more detailed study of monolith channel flow and its transport characteristics and attempts to couple a CFD and chemistry solution for a single representative channel. The experimental channel studies are described below. However, recent data [13] illustrates the attraction of the lumped parameter approach especially where unusual monolith designs or channel geometries are involved that are not suited to simple representation via the literature.

Coupled chemistry with CFD is potentially very powerful. It can accommodate different reaction schemes for multi-component fuels like syngas, deal with a range of nominal channel shape, handle heat and mass transfer mechanisms and inlet mixture strength variations. In practice, there are some areas in which there are numerical and chemistry difficulties. At a numerical level, there are issues with treatment of the extreme surface roughness present in washcoated monoliths. Predictions with considerable grid refinement do not reproduce the experimental data obtained on super-scale models. This is a situation not confined to the catalytic monolith: work in micro-scale heat transfer has been concerned with this issue for some years [14, 15]. In numerical terms, there are difficulties with unvalidated lean mixture kinetics, although the ILDM method of picking preferred kinetic routes has attractions [16]. The surface reaction schemes that are available in the public domain such as SURFACE CHEMKIN require knowledge of the catalyst properties that may be difficult to obtain unless the preparation process is well-characterised. We have attempted to apply combined homogeneous phase and surface reaction schemes and continue to develop such models.

A further area modelled relates to the flow at the monolith exit. Although the channel wall dimensions are small, mixing in this region may have a role in stabilizing small zones of homogeneous combustion but, in general, the region can be regarded as being in plug flow. The issue here is then the validity of the kinetics for hydrocarbon and products consumption: reliable kinetics schemes are still needed.

### 3. Catalyst Light-off

The combination of catalyst characteristics and through-flow velocity (air loading) required by modern gas turbines means that self-ignition of the fuel:air mixture in the combustor cannot always be attained except at very high cycle pressure ratios, where the compression preheating of the mixture is large. The engine starting phase also cannot be under catalytic control. Figure 6 shows the influence of cycle pressure ratio on light-off of natural gas over Pd/PdO catalysts, with the effects of ambient temperature imposed. Figure 7 gives the corresponding preburner temperature rise necessary to obtain self-sustaining catalytic operation.

The prospect of exploiting the lower light-off temperatures of other fuels, notably hydrogen and carbon monoxide, was studied and data presented in 1997 [17]. Our study using hydrogen addition, and later carbon monoxide addition, showed that acceptable reductions in steady-state catalyst operation could be obtained with modest amounts of fuel augmentation, Figure 8. Since then, a variety of practical schemes have been proposed, some of which use off-engine fuel processing to produce syngas from the natural

gas precursor [18, 19]. Few of these enable the full range of simple cycle combustor entry temperature to be accommodated. However, where heat is reclaimed from the engine exhaust via a recuperator, self-sustaining catalyst operation can be achieved over a wider range, even for methane-based fuels. Engines aimed at small scale Combined Cooling, Heat and Power or Distributed Generation using recuperation in the cycle improve the combustor entry temperature substantially, typically to 850K for powers between 50 and 100kWe, over a wide operating band. Such cycles are optimised at lower pressure ratios than unrecuperated simple cycle machines, whether in direct open cycle or combined cycle mode, typically 3 to 6pr. This enables lower combustion temperature rises to be utilised, placing less stress on the catalysts. For small machines using uncooled radial turbomachinery, the maximum cycle temperature is ~1225K, so all the energy conversion theoretically can be accomplished in a catalytic combustor. The combination of higher combustor entry temperature and low temperature rise makes such machines an attractive catalytic combustion application for a variety of gaseous fuels, e.g. LPG, natural gas and synthesis gases manufactured from biomass or waste sources (sludge, farm waste and municipal waste). Liquid fuels are also possible.

#### **4. Flow Structure, Hydrodynamics and Transfer Processes in Monolith Channels**

The use of monolith reactors in high throughput situations at varying operating pressure and temperature, as in the GT, takes the flow from laminar, where classical solutions exist for the flow and transport characteristics, to transitional flows where data is scarce. When reactors operate on gases at high space velocities and the monolith channels are small to maximise catalyst active area and conversion, the frictional losses must be minimized. These criteria lead to low flow Mach Numbers and typical channel Reynolds Numbers of order  $10^4$  with mass transfer-controlled reactions. Production of monolith substrates whether in metal or ceramic and their subsequent coating and preparation with catalyst produces surfaces that are hydraulically rough in comparison to the channel size. The roughness of the channel and its relatively low aspect ratio (length/hydraulic diameter) in most installations means that the flow is not fully developed. It is desired to have high conversion rates with minimal reactant slip and maximum catalyst durability, coupled with fractional pressure losses across the entire combustor of about 3% of the total pressure.

The cross-sectional shapes of monolith channels impose specific flow characteristics on the developing turbulent flow. For non-circular shapes, e.g. square or triangular, deceleration of the flow in the corners of the channel produces sets of secondary flow vortices that significantly affect the transport of heat and reactants, [20]. Flow development in smooth channels of square cross-section has been experimentally investigated for several Reynolds Numbers between 40000 and 250000, [21, 22]. Axial and secondary flow development has been examined in rib-roughened square channels in the fully developed, rough, regime where the friction factor is independent of the Reynolds Number [23]. Detailed investigations of structure with discrete roughness elements are also available [24], but except for measurements of the mean velocity in commercial, rough, circular pipes presented in [25], the influence on flow development by random roughness in rough ducts has attracted little attention. Our studies are based on Reynolds Similarity applied to a superscale (x15) channel with walls roughened randomly to simulate a coated

cordierite monolith [26]. The channel was square in cross section with rounded corners to represent the catalyst wash coat. Leading particulars are: channel side wall 15mm; aspect ratio 70; corner radius 3mm; hydraulic diameter 15.85mm; relative roughness (experiment)  $2.5 \times 10^{-3}$ ; relative roughness (monolith)  $5 \times 10^{-3}$ . Roughness is defined by the average peak/valley dimension averaged over an increment of the channel length and was measured by laser methods for the cordierite sample and model.

$$R_a = \frac{1}{\Delta x} \int_0^{\Delta x} y(x) dx$$

The experimental Reynolds Number was  $10^4$ , isothermal flow. A smooth wall, square cornered channel of the same general size was studied to provide data free of surface and corner radius effects.

The experiments used two-component Laser Doppler Anemometry (LDA) through 17 quartz windows along the channel length with backscatter measurement for mean and fluctuating velocities. Pressure drop measurements were made along the duct also.

The Reynolds Number range for flows in small monolith channels, coupled with the aspect ratio of those channels, means that the flow cannot be regarded as fully developed except towards the end of the channel. The flow structure and its interaction with wall roughness produced by coating and the intrinsic physical condition of the monolith wall is a major influence on flow development and therefore on heat and mass transfer. Figure 9 shows the centreline mean and fluctuating velocity development in the square, rough-wall channel.

The flow is characterised by the gradual development of pairs of secondary flow vortices across the diagonal axes of symmetry of the channel. The corner radius has a significant influence on development of the flow and boundary layer thickness. The secondary flow structure in channels with sharp corners produces enhanced fluid momentum transfer into the corner region, but the presence of corner radii reduces the laminar sub-layer thickness, thus improving heat and mass transfer into the corner. In consequence the wall shear stress is more uniform and more even heat flow would be expected where there are chemical reactions at the wall. Some velocity data and the flow development are given in Figures 10, as profiles of mean and fluctuating streamwise velocity. The distortion due to the secondary flows is pronounced towards the channel exit.

The secondary flows also increase the friction factor for the channel, which is strongly dependent on roughness. Increased roughness makes the initial flow development in the channel less dependent on Reynolds Number. The interaction between channel shape, corner radius and wall roughness may be important in designing monoliths for a wide range of flow whilst reducing thermal stress in the structure and flow pressure losses. Wall roughness exceeding the laminar sub-layer thickness (smooth wall) influences the transport throughout the duct in isothermal conditions: where energy is liberated in the boundary layer, matters may be different.



The tripped flow at the channel inlet enhances the inlet heat and mass transfer rate in the developing flow region and so may raise chemical reaction rates in this zone, leading to additional thermal stress in this region. Small modifications to the square edge condition will affect this conclusion, as will large web thicknesses between channels.

### Pressure Drop

Static pressure data shows the boundary layer is already in a reattached state and redeveloping at about 2 hydraulic diameters downstream of the inlet plane. The initial development of the wall boundary layer covers about 6 hydraulic diameters and thereafter becomes fully developed. An overall friction factor for the channel, based on corrected cross sectional area, was established at  $9.23 \times 10^{-3}$ , defined as

$$C_f = \frac{1}{2} \frac{\Delta p D_h}{L m^2} \rho A^2 \quad \text{where}$$

$L$	= channel length	$m$	= mass flow
$A$	= cross-sectional area	$D_h$	= hydraulic diameter
$\rho$	= fluid density	$\Delta p$	= pressure loss

This is somewhat different from the correlation given elsewhere [21, from] Beaver, Sparrow & Lloyd, for a smooth square duct, which gives  $C_f = 8 \times 10^{-3}$ .

For a fully rough flow regime a friction factor greater than  $2 \times 10^{-2}$  would be anticipated, and the difference between this value and the value obtained from the measurements confirms that the flow in this case is mainly in transition, and that the thickness of the (smooth wall) laminar sub-layer is roughly the same order of magnitude as the roughness height, ie about 200 $\mu$ m. The surface roughness is close to the laminar sub-layer thickness and in places exceeds it: where this occurs the boundary layer is perturbed and the turbulent fluctuations propagate downstream to the channel centre line. The roughness in the experiment was half that of a coated ceramic monolith simulated.

### 5. Concluding Remarks

The Group's experience now extends over forty man-years of effort. It has concentrated on the thermo-physical aspects and description of the catalytic combustion process. We have recently invested in a person with catalyst chemistry skills, an investment that underlies the perceived importance of the technique: we are a small group that cannot afford too broad a spectrum of strategies. Although the technique is reaching market application – the first lengthy operation on a gas turbine delivering useful power from natural gas is available on the world-wide web (Catalytica Inc) – there remains much to do to gain acceptance. One of the more attractive niches relates to the reaction-tailoring capability of catalysts for such problems as FBN. There are, of course, still issues with catalyst activity, catalyst and substrate durability, life, dynamic response of catalytic combustors, their start-up and user acceptance.

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  - High Flow: 24bar and 4.3kg/s, steady flow, from two compressors.
  - New low flow system to 40bar, 0.45kg/s now being installed.
  
2. Air Heaters
  - Steady flow, indirect-fired, unvitiated to 740K (approx 20pr simple GT cycle equivalent) usable to 17bar 5kg/s flow: mostly applied to GT combustor research and industrial combustors.
  - Discontinuous, unvitiated, Pebble Bed, to 1800K, 16bar, flows between 0.5 - 2.2kg/s with operating durations ~ 15 - 45mins depending on flow rate.
  - Typical applications are: simulation of high stagnation enthalpy flows
  - (~ M2) for high flux heat transfer; supersonic combustion or high inlet temperature combustors. eg regenerative GT cycles and High Temperature Air Combustion (HiTAC).
  
3. Fuel Supplies
  - Liquid
    - Jet A1
    - No2 Distillate
    - Heavy blends
    - Special fuels
  - Gaseous
    - Line Natural Gas and blends
    - Low and Medium CV gases based on CO, H2, CH4 with N2, CO2 and H2O ballast
    - All to 12MWt, extendable
  
4. Instrumentation
  - Gas Analysis
    - Dedicated single-species analysers for CO2; CO; UHC; NOx; O2; H2O
    - FTIR Spectrometer, 40+ library spectra
    - Mass Spectrometer to 100 amu, configured for moist gases and He tracer
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    - All thermocouple types
    - Liquid crystal thermography
    - Thermo-chromic paints
    - Optical Diagnostics
      - Single pulse and averaged LIF for single & two-phase gas & liquid mixing, e.g. for fuel/air mixing & sprays
      - Chemical component, e.g. OH radical for reaction progress variable
      - 2 Dimensional LDA
      - PDA for two phase measurements, especially sprays
      - Schlieren
      - Planar laser tomography

Table 1 Experimental Capabilities and Facilities for Combustion Research in the School of Engineering.

Dates	Project Funding Agencies and approx. value	Partners	Fuel	Applications
1991-1995	LINK New Catalysis and Catalytic Processes. £1.8M Catalytic Combustion	Rolls-Royce Plc., Johnson Matthey Plc and University of Bath, R-R led	Natural Gas	Use of line natural gas in aero-derived industrial gas turbines for power production
1997-2001	Foresight Challenge Round 1 Catalytic Combustion £2.2M	Alstom Power and Queens University Belfast, Cranfield led	Biomass and coal derived synthesis gases	IGCC gas turbines, all sizes
2001-2004	EPSRC Catalytic Combustion £258k	University Texas	Any gaseous	Generic
2003-2006	European Union Catalytic Combustion £290k	14 Partners led by Alstom UK	Natural gas	Industrial gas turbine power production
2002- 2005	Turbulent flame speed measurement £220k	22 partners led by Alstom UK	Natural gas	CCGT power
1999- 2002	UK HEFCE £1.3M	none	any	Plant refurbishment
1991- 2002	Various Company PV total greater than £1M, mostly turbulent flame applications	none	Liquids & Gas	Variety of combustor and heat transfer applications for aero and industrial use

Table 2 Some Collaborative and Private Venture Funded Projects in the Combustor and Heat Transfer Technology Group over the last 10 Years.

Biomass gas composition tested (vol. %)					
N <sub>2</sub>	H <sub>2</sub>	CH <sub>4</sub>	H <sub>2</sub> O	CO <sub>2</sub>	CO
52-65	12-15	2	0-4	6-8	19-21

Test conditions : Pressure 313-343 kPa, linear velocity 10 m/s, ~2% O<sub>2</sub>

Table 3 Fuel Gas Composition for Ammonia Conversion Experiments [11].

## Conversion

NH <sub>3</sub> (ppm)	T (°C)	P (kPa)	GHSV* (x10 <sup>6</sup> h <sup>-1</sup> )	GHSV** (x10 <sup>5</sup> h <sup>-1</sup> )	NH <sub>3</sub> conv. (%)
3000	688	313	3.1	6.9	91
3000	683	313	3.2	7.2	90
3000	684	323	3.3	7.2	95
2000	684	333	3.3	7.2	93
1400	687	333	3.3	7.3	89
1400	687	338	3.3	7.2	87
1400	683	328	3.3	7.2	72
1400	690	328	3.3	7.2	73
1300	680	323	3.3	7.2	61
1300	746	338	3.5	7.6	52
1300	762	343	3.5	7.6	67

\*Reactor 1, \*\* Reactor 2, both at operating condition

Table 4 Ammonia to Nitrogen Conversion, [11]

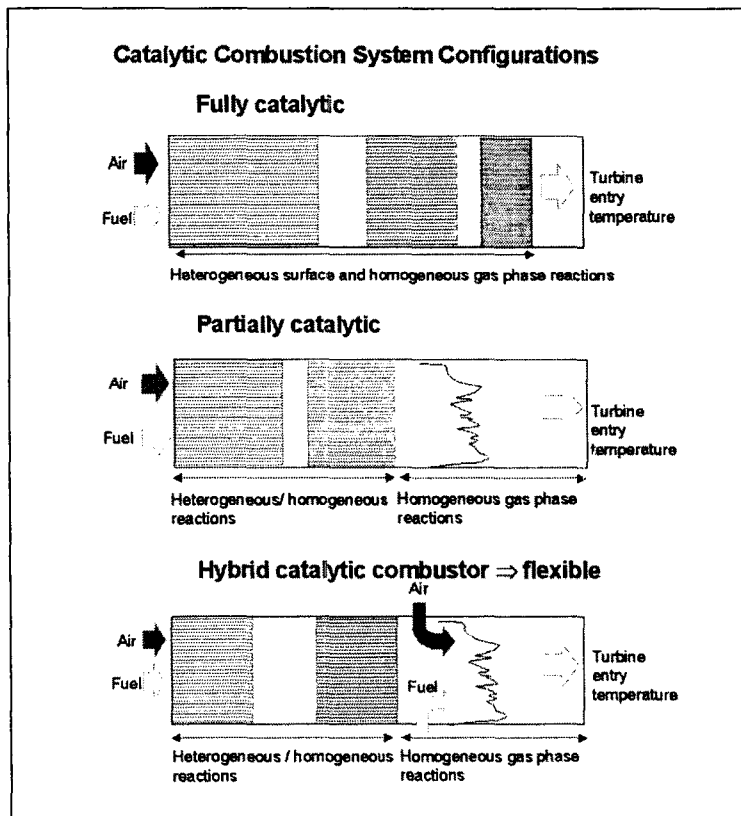


Figure 1 Schematic Arrangements of Catalytic Combustor

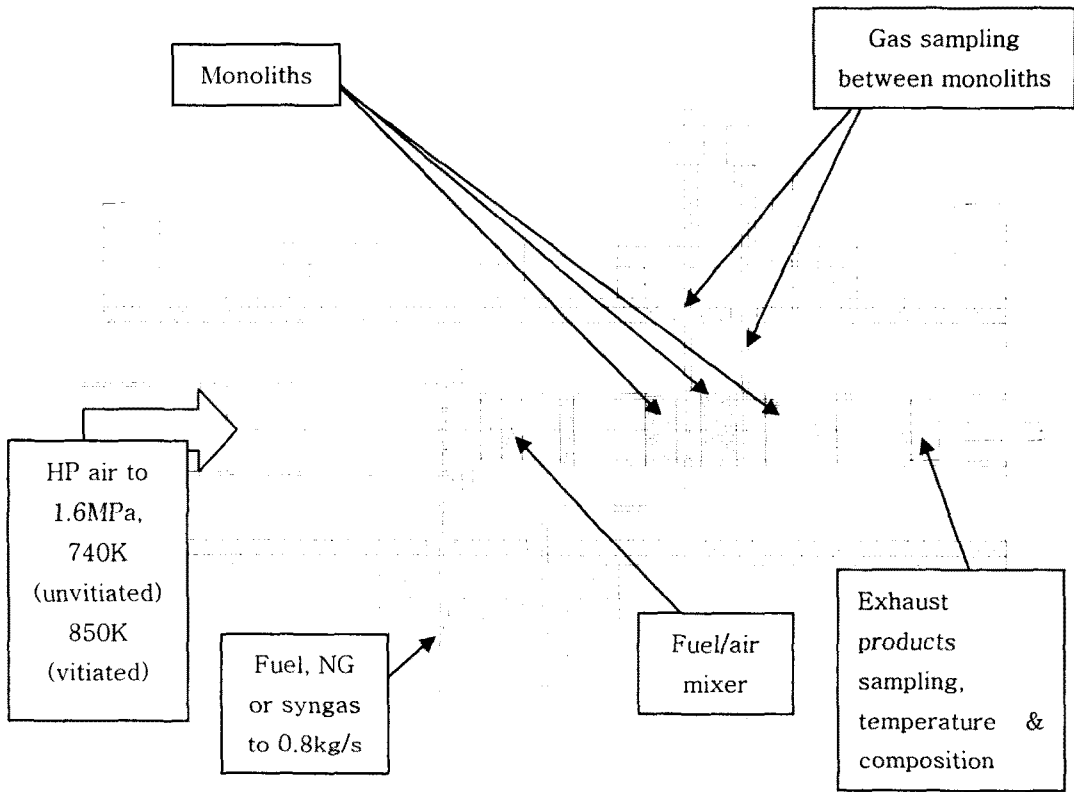


Figure 2 Generic Catalytic Combustion Rig for 'Simple' & Staged Configurations.

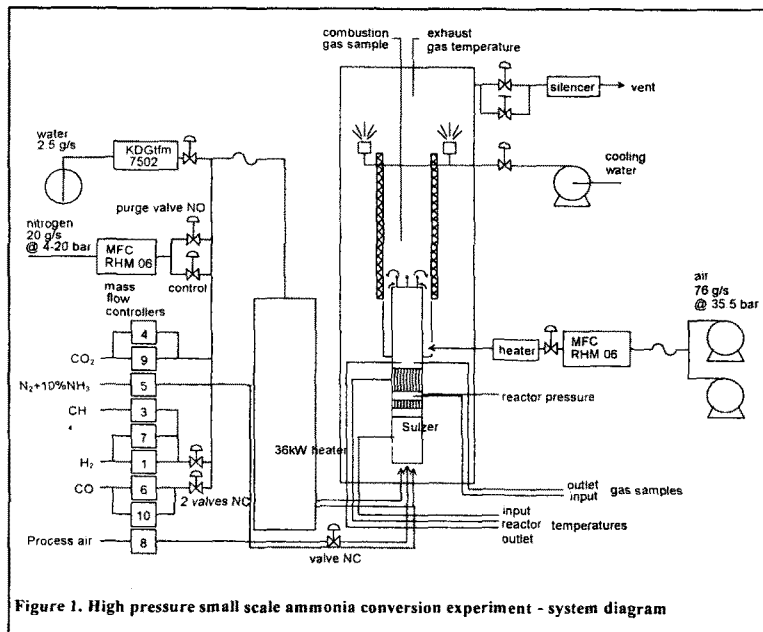


Figure 1. High pressure small scale ammonia conversion experiment - system diagram

Figure 3 Air and Fuel System for Ammonia Reduction Experiments [9, 10, 11].

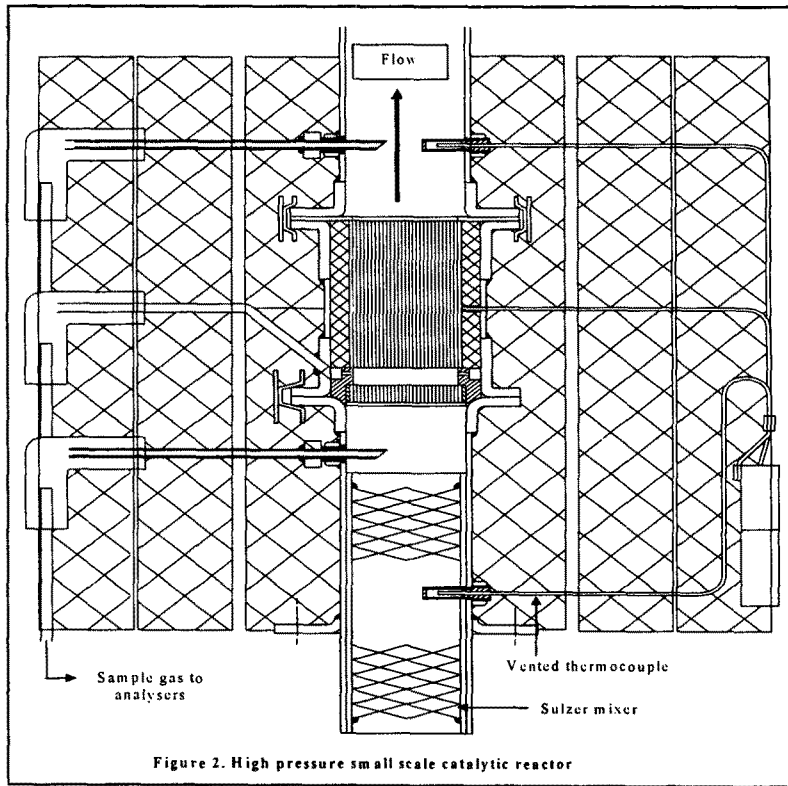
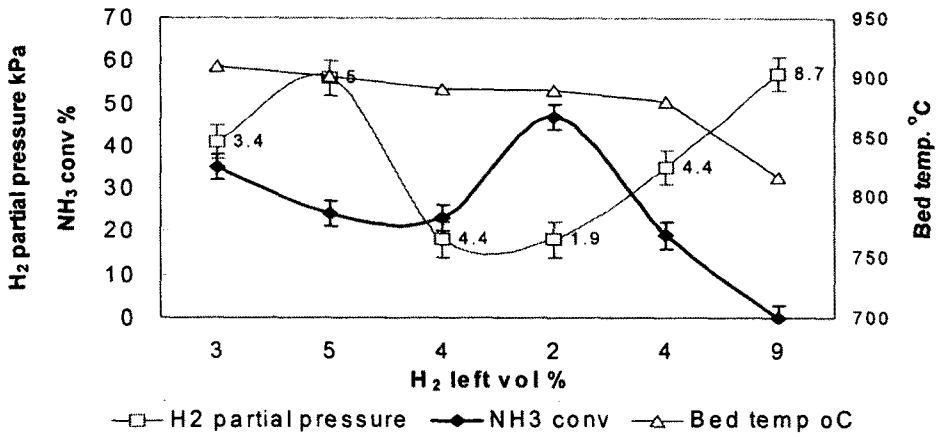


Figure 4 High-pressure Catalytic Reactor for Ammonia Reduction Experiments [9, 10].





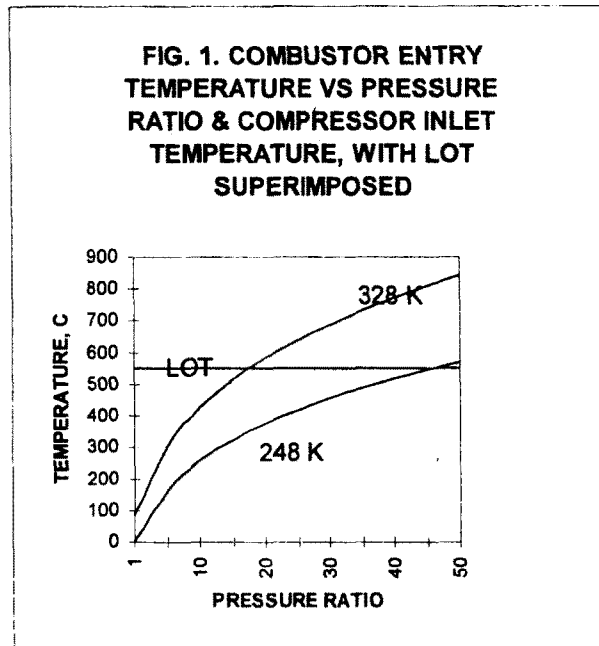


Figure 6 from [17], showing a range of combustor entry temperatures, based on ISO 2314 (baseline 288K)  $\pm$  40K, with typical Pd/PdO catalyst characteristics Light-off temperature (LOT) superimposed. The Figure is simplified.

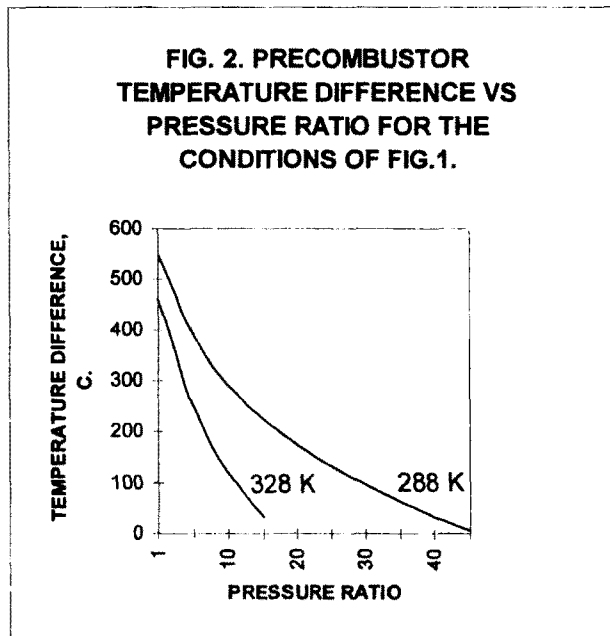


Figure 7 Temperature rise required from a preburner, for the conditions of Figure 3, taken from [17].

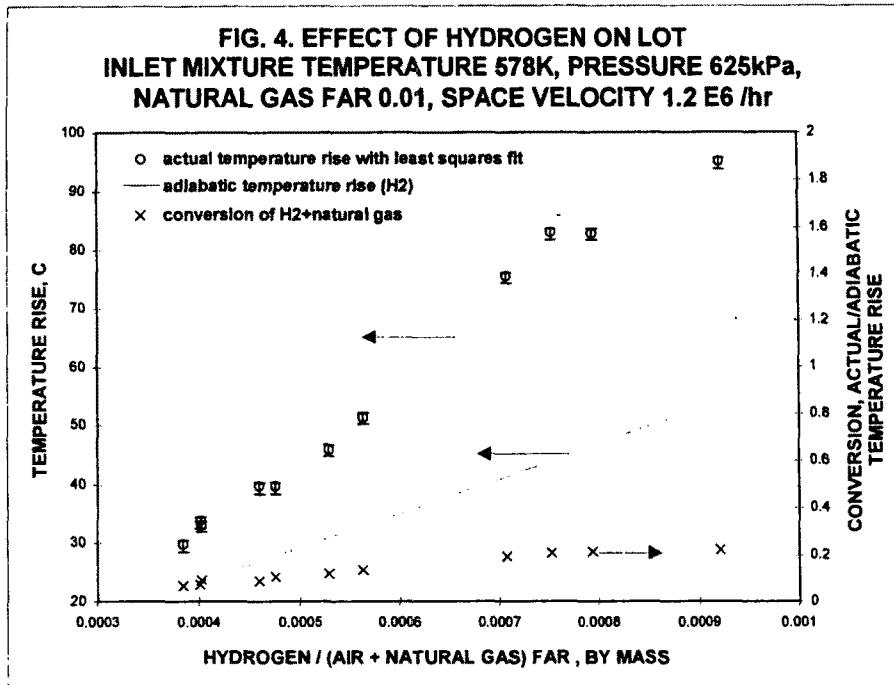
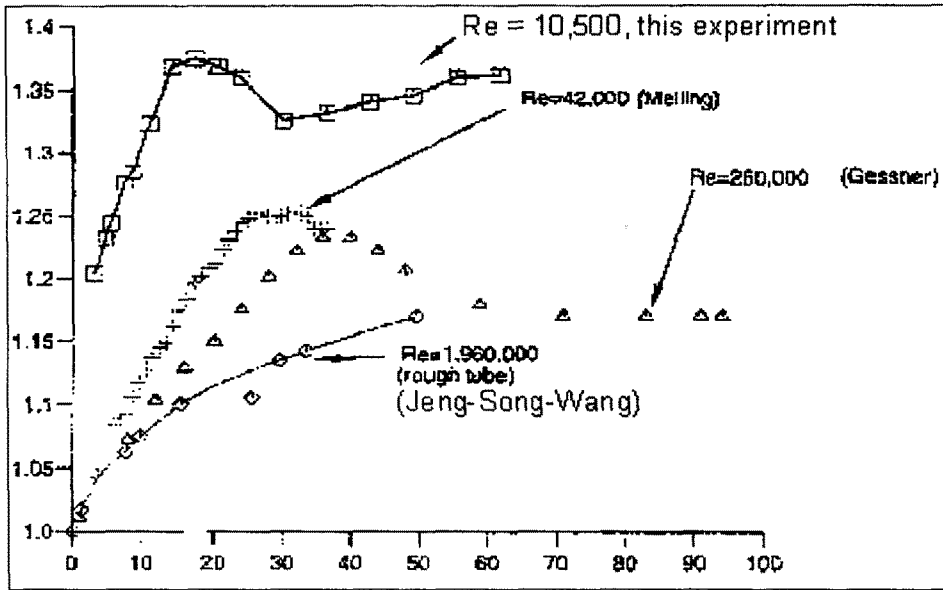
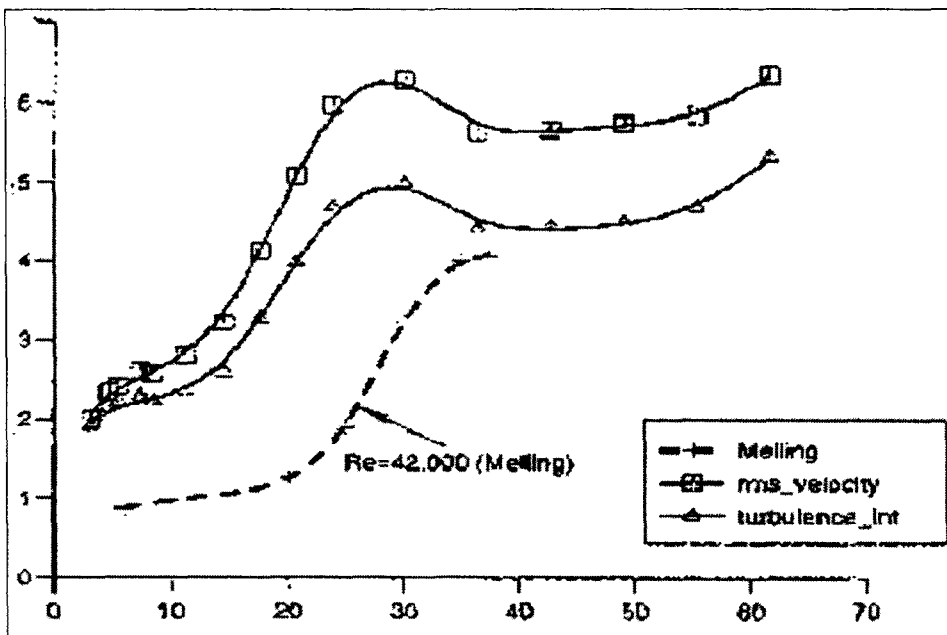


Figure 8, taken from [17]. Variation of catalyst light-off temperature (LOT) for Pd/Pt catalyst with Hydrogen addition to natural gas.



Centreline to Average Velocity vs Channel Aspect Ratio,  $L/D_h$



Centreline RMS to Average Velocity Ratio and Centreline Turbulence Intensity vs Channel Aspect Ratio,  $L/D_h$

Figure 9 Rough Wall Monolith Channel Flow Development, taken from [26].

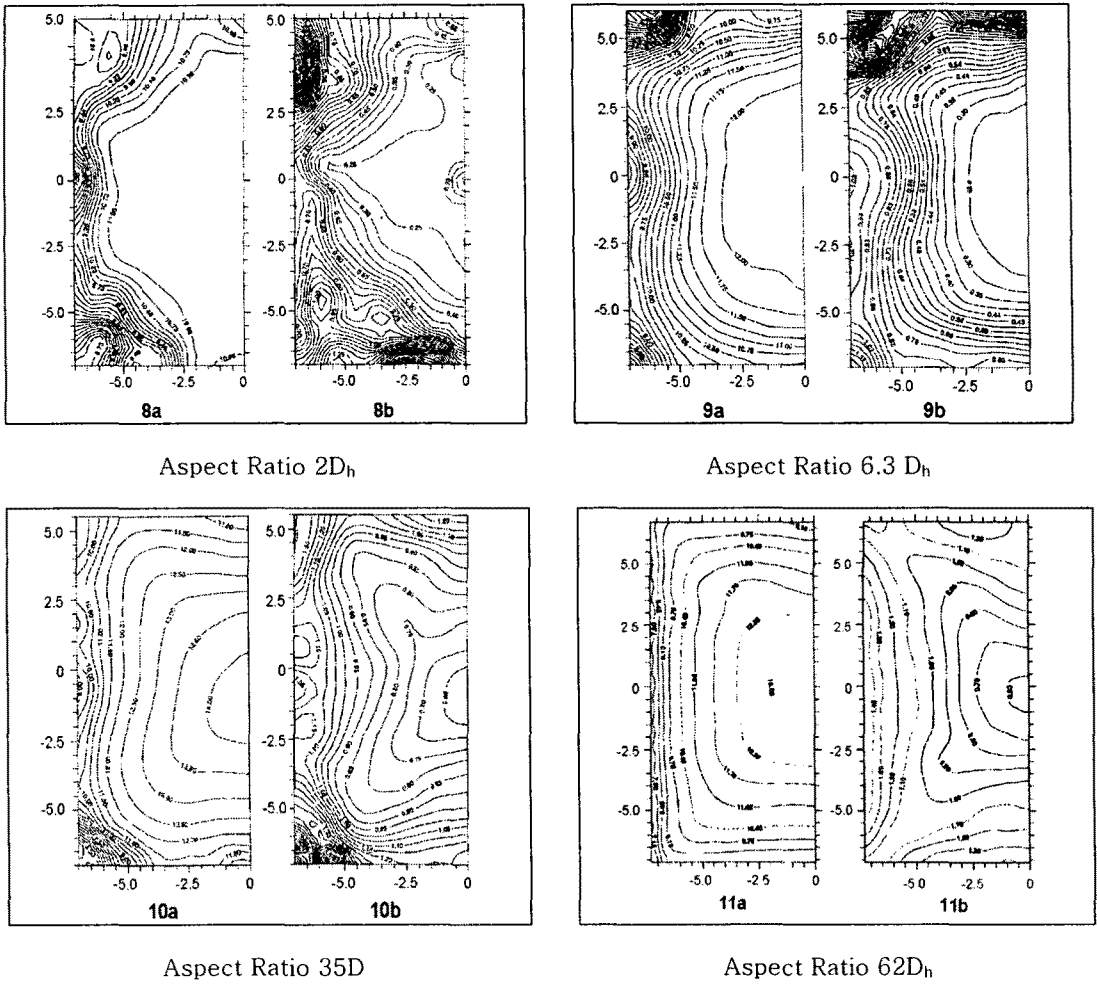


Figure 10 Flow Development as Axial Velocity Profiles at Different Aspect Ratios,  $L/D_h$ , along the Rough Wall Channel, showing the Secondary Flow Evolution, from [26].