FLUIDIZED BED COMBUSTION RESEARCH AND DEVELOPMENT IN SWEDEN – A HISTORICAL SURVEY

by

Bo LECKNER

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A survey is made on research and development related to fluidised bed boilers in Sweden during the past two decades, where several Swedish enterprises took part: Generator, Götaverken, Stal Laval (ABB Carbon), and Studsvik. Chalmers University of Technology contributed in the field of research related to emissions, heat transfer and fluid dynamics, and some results from this activity are briefly summarised.

Key words: combustion technologies, fluidized bed combustion, boilers, research and development

Background

The motives for combustion research and development differ from country to country depending on the energy supply and demand situation and political preferences. In order to understand the Swedish situation, it must be realized that the electric energy demand is satisfied by about equal parts of hydro power and nuclear power. For this reason there are no recent power stations based on combustion. On the other hand, a large part of Sweden's energy supply is directed to space heating supplied by district heating systems. Therefore, the large scale plants of interest in connection with combustion in Sweden are not utility boilers but district heating and industrial boilers for heat or combined heat and power production.

After the Second World War there was a rapid increase in the use of oil, and solid fuels were abandoned. The oil period ended in the 1970s as a consequence of the rising oil prices, which stimulated the conversion from oil to various energy sources and to saving energy. After the Swedish referendum in 1980, in which it was decided to phase out nuclear power, it became clear that coal was preferable as a primary source of energy for existing boilers as well as for possible future electric utility boilers, which would be needed to replace nuclear power. A comprehensive investigation 1 stated that coal was environmentally acceptable, and the use of coal could increase. In the beginning of the 1990s, under the impression of the threatening greenhouse effect, coal again became unacceptable and the use of biofuels was encouraged by a suitable taxation 2. Figure 1 shows the price relations between various fuels with and without tax. The figure contains



Figure 1. Electricity production costs for new cogeneration plants with and without taxes $\ 2$

part of the explanation for the substantial use of biofuels in Sweden that followed – biofuels became cheaper than other fuels because of taxation. The other parts of the explanation were the availability of wood waste in the forests and the suitable size and location of the district heating plants.

So far there is little natural gas in Sweden, but a certain interest has been shown from neighbouring countries (Norway, Russia (across Finland), and Denmark) for an increased supply of natural gas. In summary: there was an oil period 1950-1975, a coal period 1975-1990, and a biomass period starting from 1990. Will the next period be a gas period?

In the end of the oil period the government in Sweden, as well as in other countries, decided to actively support research and development to reduce the strong dependence on oil consumption. In the programme area related to combustion in large-scale plants this activity focussed on the utilisation of solid fuels in district heating and industrial boilers. A considerable development and research activity was initiated.

Boilers

As will be seen, the problem area is even more limited than to district heating and industrial boilers in general. It also depends on the degree of technical development of possible combustion devices and the environmental requirements. There are three ways to burn solid fuels: combustion of pulverised fuels in suspension (flame), combustion on grate (fixed or moving bed), and combustion in fluidised bed.

Compared to the other methods, fluidised bed combustion (FBC) was not at all developed in the 1970s, but it was deemed to be a promising technique having properties that suite the Swedish requirements: inherently low emission levels and fuel flexibility.

Therefore it was natural to focus attention on FBC. The research and development activity related to FBC took place at Chalmers University of Technology (CTH), Studsvik Energy AB, and in the boiler manufacturing companies Götaverken and Generator (Later they were united under various names. At present the name is Kvaerner Pulping AB, including also the Finnish company previously called Tampella). Stal Laval developed a boiler to fit their gas turbine, a pressurised fluidised bed combustor (PFBC), and the company ABB Carbon was formed for this purpose. At the turn of the century this activity was sold to Alstom.

Early designs

An application for economic support to build an FBC boiler was submitted by Generator AB and CTH in 1977. Three years later a grant was given by the government to build a demonstration plant. This unit should also serve for heating of the university and it could be used as a research plant. The boiler, put into operation in 1982, is seen in fig. 2. This 16 MW_t steam boiler has many innovative features: the bottom is sectioned for load control by bed "slumping", in-bed heat exchangers in the form of wings extended from the membrane-tube walls, a start-up combustion chamber was located be-

low the bed, etc. A thorough description is found in ref. 3. The fluidisation velocity was initially 2.5 m/s at full load. Various fuels could be used, but coal was the design fuel. It soon became evident that the in-bed tubes were severely eroded by the bed. All wing-tubes in the bed, but not those of the superheater needed for steam production, had to be removed and the boiler was de-rated to 10 MW. Metal coatings to extend the lifetime were then applied to the superheater, as well as to the remaining vertical tube-walls. Another lesson learned was that recirculation of ashes was necessary during combustion of coal to obtain an acceptable combustion efficiency. A multiclone filter was available, from where some recircula- tion of ashes could have been achieved, but erosion and plugging affected its performance. However, the initial problems were overcome and the boiler was operated without some heat transfer surface at reduced load (lower fluidisation velocity) for several years until 1990, when a new fluidised bed boiler was put into op-



Figure 2. The 16 MW FBC boiler at Chalmers University of Technology 3



Figure 3. The 12 MW (8 MW maximum continuous rating) CFB boiler at Chalmers University of Technology 4



Figure 4. Layout of a 35 MW CFB boiler based on the Studsvik prototype 5

1 – fuel feed, 2 – secondary air supply, 3 – combustion chamber, 4 – U-beam separator, 5 – cyclone for final particle separation, 6 – convection path, 7 – settling chamber for ash separation, 8, 9 – ash recirculation arrangement

eration, this time a circulating FBC (CFBC) designed for research, but also, as previously, for heating of the university. A picture of the 12(8) MW_t CFB boiler is presented in fig. 3.

At about the same time Studsvik developed an alternative CFBC, fig. 4, which contained many unique design elements: a U-beam particle separator to avoid the expensive cyclone, an L-valve reinjection for controlled particle circulation to adjust the particle inventory in the bed, and a furnace with a particular shape 5. The design attracted the attention of Babcock & Wilcox to the extent that they bought a licence. More than ten boilers were produced according to this concept, but Babcock & Wilcox developed the design further and today mostly the U-beam separator, converted to an internal separation device inside the furnace, remains from the original design 6. The idea to replace the conventional cyclone can now be seen in several other designs.

To make the picture complete it should be mentioned that Götaverken also started development of CFBC in the beginning of the 1980s. Figure 5, taken

> from a patent application, gives an idea of their design. Götaverken was successful in rapidly introducing their product on the market, encountered a great deal of difficulties of operation, but solved the problems and had a mature design at the end of the decade. This company also developed a CFB gasifier for biomass to be used in the pulp and paper industry to replace oil, fig. 6. One commercial plant was successfully put into operation (Värö bruk) before the oil prices again fell and made this type of gasifier less interesting. This plant is still (2003) in operation, however.

> Already at the end of the 1960s and in the beginning of the 1970s Stal Laval was developing a fluidised bed superheater to be installed in ship machinery ("very ad-

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Figure 5. Principle drawing of Götaverken's CFB boiler taken from a patent application 7

The main parts: 10a – membrane tube heat receiving surface, 11 – air distributor, 13 – ash removal system, 15 – secondary air nozzles, 17 – fuel feed, 18, 19 – solids recirculation duct, 21 – cyclone, 22 – loop seal, 25 – convection path, 30 – char/bed material separator

vanced propulsion system"). The change in oil prices stopped the introduction of such a device on the market. However, the knowledge and the interest for fluidised bed remained, and Stal Laval realised that their gas turbine would be quite fitting in a combined cycle power process, where the heat source for both the steam and the gas turbine cycle could be a pressurised fluidised bed. This system was developed during the 1970s and the 1980s, but only in 1987 a decision was taken by Stockholm Energi to build a



Figure 6. Gasifier for biofuels built by Götaverken



Figure 7. The pressure vessel of a PFB containing the combustor 8

plant in Värtan. At about the same time power companies in Spain and in the USA decided to build plants of the same type for evaluation of the technology in practice. An example of a pressurised FBC (PFBC) is seen in fig. 7, showing the combustor with its immersed boiler tubes, cyclones and other arrangements inside the pressure vessel. The year 2003 the Värtan plant is still in operation, the Spanish plant is operated occasionally as part of the power system, and the American plant is dismantled.

Investigations

What has been learned about the combustion behaviour of FBC? Focussing attention on the work at CTH there are three major subject areas: emissions, heat transfer, and fluid dynamics. A general review of this problem area, including the work at CTH, has been published 9. Here a few comments will be made.

Emissions

The aim of the investigations on emissions was to show the emission properties of an FBC, and if possible, to explain the mechanisms behind the emissions. The early results have been summarised in 10. The following observations were made:

The emissions are influenced by a great number of boiler operation parameters. This is what makes FBC interesting; there are several promising ways to go for optimisation.

Bed temperature and excess air are the two most important parameters to influence the NO emission during combustion of coal, but they are not efficient during combustion of biofuels 11 . The explanation for the insensitivity of an FBC burning biofuels is most likely found in the small char content of the bed for such fuel, ten times less than for coal. Char is a principal reducing agent for NO and its content is affected by fuel type, temperature and oxygen concentration.

CFBC tends to promote the conversion of fuel nitrogen to NO for high volatile fuels, whereas stationary fluidised bed combustion (SFBC) shows an opposite trend. The explanation of this behaviour remains to be found. This is a task for ongoing work.

The conversion of fuel nitrogen to NO emitted is almost independent of the fuel nitrogen content because destruction is related to the combustion situation, and destruction dominates over fuel dependent formation. An extreme example is that wood, whose nitrogen content is small, yields an emission of the same magnitude as coal, whose nitrogen content is much greater (CFB conditions).

It was discovered that N_2O is emitted from FBC but not significantly from other combustion devices. The explanation is that the temperature range of operation of FBC is favourable for formation of N_2O at the same time as reduction is slow.

The emission of N_2O is related to air excess just like that of NO but the influence of temperature is reversed, fig. 8.

The bed material has a catalytic influence on certain reactions in the bed. For example: the NO emission rises when limestone is added for sulphur capture. Particularly, porous CaO is active in conversion of ammonia 13, but most of the CaO surface is deactivated by CaSO₄ formed by sulphur capture. CaSO₄ has an insignificant effect



Figure 8. Influence of bed temperature on the emission of NO and N_2O during combustion of coal in a 165 MW boiler in Örebro $\,\,12$

on the reactions forming NO. So, during an excess addition of limestone the NO emission increases dramatically because of the larger availability of unreacted CaO. CaO also contributes somewhat to the reduction of N_2O , see fig. 8.

A comprehensive work to understand the factors influencing the N_2O emission resulted in proposals of several reduction methods 14, 15.

The well-known temperature dependence of sulphur capture was studied. (There is an optimum of sulphur capture at 850 °C and this is one of the reasons why FBC is most frequently operated at this temperature). The reason for the temperature dependence was explained to be local and temporary reducing conditions in the bed, despite total excess air 16, 17.

As a consequence of this insight and knowing the thermodynamics of the system: SO_2 , O_2 , CaO, CaS, and CaSO₄ it was possible to explain the sulphur capture behaviour of different types of FBC operating with different types of fuel.

Heat transfer

There is an overwhelming number of correlations published on heat transfer to surfaces in bubbling fluidised beds. The problem has been approached in two ways: (1) by mechanistic models, such as particle replacement models, or (2) by correlations, the

simplest and most useful one being Zabrodski's formula. However, no heat transfer relationship helps if the fluid dynamic situation at the heat transfer surface is not understood. The background to this remark is that almost all work on heat transfer in FBC is based on experiences from laboratory equipment and the corresponding results can not readily be transferred to the situation in a combustor bed. There is a very limited experience reported from large-scale combustors. A striking example from the 16 MW boiler at Chalmers is shown in fig. 9. The heat transfer to the walls surrounding the bed is highest at the surface of the bed and declines upwards, not surprising, since the particle density declines upwards. It is more surprising that it also declines downwards from the surface, obviously dependent on the movements of the bed, the same movements that cause erosion on the heat transfer surface, as illustrated by the accompanying diagram of fig. 9. It is not possible to estimate this behaviour by means of available correlations.



Figure 9. Material loss due to erosion (left diagram) and heat transfer coefficient (right diagram) to the wall of a bubbling bed [18]

However, the stationary FBC was abandoned for coal combustion, and instead subsequent attention was directed towards CFB, where heat transfer to the vertical wall surfaces would avoid erosion. The results obtained at Chalmers were compared with the few other data published from boilers and hot research units, Fig. 10, and the question was asked: "do we know sufficiently?" 19. Integrating along the height of the combustion chamber these data can be further reduced 20:



Figure 10. Heat transfer coefficients measured under hot conditions vs. cross-section average suspension density [19]

$$\alpha = 110\rho^{0.21} \tag{1}$$

where α W/m², degree is the average heat transfer coefficient over the entire wall consisting of heat transfer surface, calculated as projected surface. The suspension density ρ kg/m³ is an average over the corresponding furnace volume.

All information available is condensed into eq. (1) which is valid for heights between 2 and 20 m. The obvious simplifications are contained within the limits of accuracy of the data. If this information is sufficient for the manufacturing industry, then the answer to the question is yes. If eq. (1) is not sufficient, then work should be done to further explain the mechanisms of CFBC heat transfer and, because of the strong connection, of fluid dynamics.

Fluid dynamics

As long as fluidisation studies are restricted to low fluidisation velocities they can conveniently be carried out in small laboratory equipment. When the velocity increases, the bubble size increases and eventually the bubbles become restricted by the equipment. This dilemma is significant in CFB, operated at high velocities, for which large cross-sections are quite difficult to handle in the laboratory. As a result, most research work related to CFB is carried out in tall but narrow test tubes. Examples from different equipment are shown in fig. 11.

These test tubes differ from combustors in the sense that the latter have large cross-sections. For this reason fluidisation is seen from different angles in the two types of equipment. The research at Chalmers has been fortunate to have access to large-scale equipment, thus avoiding the wall effects. Three regions of the riser have been studied: the bottom bed, the splash zone, and the transport zone.

Despite the high gas velocities of the CFB a dense bottom bed is maintained, and its behaviour was found to be similar to a bubbling bed 22, 23. The explanation is that all bed particles do not experience the high velocities, because of by-pass of gas through the bubbles. Above the bottom bed there is a splash zone, formed by particles thrown up by the movements of the bottom bed. In this zone there is a high reflux of particles. The resulting profile of particle concentration versus height is exponential and extends a meter or two



Figure 11. Vertical measurement position and total riser height for boilers (cases above the dashed line) and laboratory risers, both related to the riser diameter [21]

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from the bed. The exponential decay is characterised by a "decay coefficient", similar to what has been observed previously in bubbling beds 24. This is not surprising, considering the bubbling character of the CFB bottom bed. Above the splash zone particles are carried away with the gas, but there is a continuous separation of particles into the wall layers of descending particles. Also in this region the exponential decay of cross-section average particle density can be characterised by a decay coefficient. The cross-section average density profile can thus be described by two exponentials 24. The corresponding particle fluxes can be evaluated and in this way, based on empirical data, the particle flows can be calculated. Figure 12 illustrates the result of an estimation of the (externally) circulating flux G_s kg/m²s and corresponding fuel flows: fuel feed flow F_x kg/m², internal circulation flow $9F_x$ and the external circula-



Figure 12. Example of solids (fuel) flows in a CFB furnace [25]

tion flow $3F_x$. It is interesting to see that the internal recirculation of fuel particles is 3 times greater than the external one and 9 times greater than the fuel flow in this example.

The narrow risers and the wide combustors are similar in the respect that in both cases there is an upward particle flow in the core of the riser and a downward flow of particles at the wall 26. However, measured horizontal flux profiles differ in shape: they are flat in boilers and parabolic in narrow risers. The explanation [24] is most likely that the low aspect-ratio boilers are in a developing flow regime, in analogy with single-phase duct flow, whereas the narrow risers have already a developed flow at the level where measurements are usually made (fig. 11).

In conclusion, a description of the basic fluid dynamic features of a combustor has been achieved. There are qualitative similarities with the commonly published data from narrow risers, but there are also fundamental differences.

Trends

In the field of electricity production from large utility plants there is a trend in Europe and perhaps elsewhere to plan for use of natural gas in large, highly efficient combined cycle power plants, built on the basis of available techniques. In the second place there is a competition between (highly efficient) pulverised coal, single cycle, plants and combined gasification/combustion gas/steam turbine cycles, where fluidised beds are suitable both for the gasifier and for the combustor (in the case of a combination of both). The fuel would be coal.

On the small and intermediate scale (but still large in the sense of this paper) district heating and industrial plants the situation is more diverse: in most cases "normal" fuels will be used, but there is a strong tendency towards the utilisation of "new" fuels, such as wastes and biofuels, as primary fuel or in combination with a conventional primary fuel: co-combustion. In the latter field of application FBC is a strong candidate, because of its fuel flexibility and if severe environmental restrictions are imposed.

Tasks for research are difficult to generalise, but if combustors are sorted up into known technique, new technique, and proposed technique, quite obviously the approaches are different.

In the case of known technique (flame combustion, grate combustion) there is a need for predictive methods in order to achieve a better design of combustion chambers with respect to reliability, efficiency and emission performance.

In the case of new technique (FBC), in addition to the above, there is a need to better understand the processes in the combustion chamber. Particularly the time-dependent character (fluctuations) of the fluidised medium should be investigated in order to treat chemical reactions, related to combustion and pollutants, not only using time-average data but with actual concentrations. In this field the increased performance of computors creates new possibilities to describe the behaviour of the two-phase medium – a key to interpreting observations.

In the case of proposed new techniques (e. g. methods to reduce CO_2 emissions) a basic evaluation of various proposals (related to combustion) is a principal task. Also here fluidised bed may play an important role 27.

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Author's address:

B. Leckner Chalmers University of Tehnology 41296 Göteborg, Sweden E-mail: ble@entek.chalmers.se

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