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# Zgorevanje v fluidiziranem sloju pod tlakom – čista premogova tehnologija
## Stanje in izkušnje

# Pressurised Fluidised Bed Combustion (PFBC) – Clean Coal Technology
## Satus and Experience

LEIF KEMMER

*Stalni gospodarski napredek je prvi pogoj za stabilnost vsake družbe. Ključ do napredka sta zagotovo pridobivanje in razdeljevanje energije. Dandanes postaja jasno, da je treba energijo pridobivati ob hkratnem izpolnjevanju zahtev po ohranjanju kolikor je mogoče neokrnjenega okolja.*

*Tri četrtine prebivalstva na tem planetu živi v razvijajočih se državah in skuša doseči višjo raven industrializiranega sveta. Ti napori so v veliki meri odvisni od razpoložljive količine energije. Edini način, kako zadovoljiti povečane zahteve, je uporaba novih bolj učinkovitih tehnologij, z večjo stopnjo izkoriščenosti naravnih virov in s sprejemljivim vplivom na okolje.*

*Tehnologija PFBC (- zgorevanje v fluidiziranem sloju pod tlakom) je prva izmed takšnih tehnologij, ki jo je treba upoštevati, je edinstven in najučinkovitejši način za pridobivanje električne energije z najmanjšim onesnaženjem okolja in brez dragih pomožnih naprav za čiščenje odpadnega plina.*

*Od starodavnih časov je premog vsestranska in najpogosteje uporabljana vrsta goriva. Dandanes premog uporabljajo za pokrivanje skoraj 40 odstotkov vseh potreb po energiji na svetu. Preostale zaloge premoga zagotavljajo, da bomo premog uporabljali kot glavno fosilno gorivo še v prihajajočem stoletju. Cena premoga je stabilna glede na cene drugih vrst goriv, kar zagotavlja energetsko neodvisnost velikega števila držav.*

*Iz tega izhaja pomen tehnologije PFBC kot rezultata dvajsetletnih intenzivnih razvojno-raziskovalnih naporov, ki so se izkazali koristne v komercialni rabi.*

*Constant economic growth is a precondition for the stability of any society. The key to progress is certainly the generation and distribution of energy. Nowadays, it is becoming clear that energy must be produced under an imperative of keeping the environment as safe as possible.*

*Three quarters of the planet's population live in the developing countries, trying to reach the higher level of the industrialised world. Such efforts are greatly dependent on the available amount of energy. The only way to satisfy the increased requirements is to use new and more efficient technologies, with a better level of utilisation of natural resources and an acceptable influence on the environment.*

*PFBC (Pressurised Fluidised Bed Combustion) technology is the first to be considered among those; it is an unique and very efficient manner of producing electric energy, with a minimum polution of the environment, and without expensive auxiliary waste gas purification devices.*

*Since ancient times, coal has been the universal and most commonly used kind of fuel. Today, coal is used for the production of almost 40% of overall world energy demand. The remaining coal resources guarantee that it will be used as the main fossil fuel during the century to come. The price of coal has remained stable among other fuel types, ensuring the energy independence of a large number of countries.*

*The significance of the PFBC technology emerges as a result of twenty years of intensive research and development, and is now proven positive for commercial use.*

## 0 UVOD

Premog je na voljo v večini držav sveta in zaloge premoga bodo, ob sedanji stopnji porabe, trajale več ko 200 let. V mnogih državah je premog ena od redkih možnosti za pridobivanje energije in pogosto edino domače gorivo, ki je na voljo. Cene premoga so stabilne kljub nemirnim obdobjem na področju energetike. Jasno je, da bo premog ostal glavni vir energije v naslednjih desetletjih. Izziv, s katerim se soočajo uporabniki in dobavitelji opreme, je, kolikor le mogoče, zmanjšati vpliv uporabe premoga na okolje.

Tehnologijo PFBC so razvijali v zadnjih dvajsetih letih in je sedaj na komercialni stopnji. Prve štiri termoelektrarne PFBC že delujejo in naročena je gradnja še dveh. Vse delujoče termoelektrarne so enotne velikosti 80 MWe pri delovanju s kondenzacijo pare. Prvo termoelektrarno PFBC z močjo 350 MWe bo na Japonskem zgradila družba Kyushu Electric.

Elektro podjetja in organizacije po vsem svetu so natančno ovrednotile izvedbo PFBC in ugotavljajo, da je zelo uporabna, z dobro obvladljivim vplivom na okolje in veliko učinkovitostjo, zanesljivostjo in razpoložljivostjo V nedavno objavljenem poročilu je EPRI prišla do sklepa, da naj bi PFBC postala prednostna tehnologija za premog z deležem žvepla pod 4 odstotki in za uporabo pri prenovi elektrarn.

Tržni in tehnološki uspeh elektrarn PFBC družbe Asea Brown Boveri (ABB) je opogumil tudi druge dobavitelje opreme, da so začeli razvijati to tehnologijo.

## 1 PROCES IN OPREMA PFBC

Termoelektrarna PFBC sestoji iz treh glavnih delov – plinske turbine, parne turbine in zgorevalnika (fluidni sloj v tlačni posodi) (sl.1). Plinska turbina daje zrak pod tlakom za fluidizacijo in zgorevanje goriva v fluidnem sloju. Premog se meša s sorpcijsko snovjo in vodo v zmes, ki jo neka vrsta betonske črpalke črpa v fluidni sloj. Le približno 0,5 odstotka snovi iz fluidnega sloja je dejansko gorivo, preostalo so premogov prah, mavec in sorbent. To je podlaga za prilagodljivost uporabe goriva pri tehnologiji PFBC in tako je v termoelektrarnah PFBC mogoče uporabljati premog skoraj vseh kakovosti.

Zgorevanje poteka v fluidnem sloju pri konstantni in nizki temperaturi (približno 850 °C), ki jo nadzorujejo cevi za pridobivanje pare, potopljene v sloj. Nizka temperatura vžiga v termoelektrarni PFBC zagotavlja, da ne pride do toplotnega nastajanja $NO_x$ in so emisije $NO_x$ že same po sebi zelo majhne. Žveplo med zgorevanjem ujame sorbent, ki ga dovajamo skupaj s premogom.

## 0 INTRODUCTION

Coal is available in most parts of the world, and, at present consumption rates, the resources will last for more than 200 years. In many countries, coal is one of the few options for power generation and often the only domestic fuel available. Coal prices have remained stable despite turbulent periods in the energy field. It is clear that coal wil remain a major energy source over the coming decades. The challenge for users and equipment suppliers is to ensure that the environmental impact from coal utilisation is minimized.

PFBC technology has been developed over the last 20 years and is now in the commercial stage. The first four PFBC power plants are in operation and two more plants have been ordered. The plants in operation today are all based on a unit size of about 80 MWe in condensing operation. The first 350 MWe PFBC power plant will be built in Japan by Kyushu Electric.

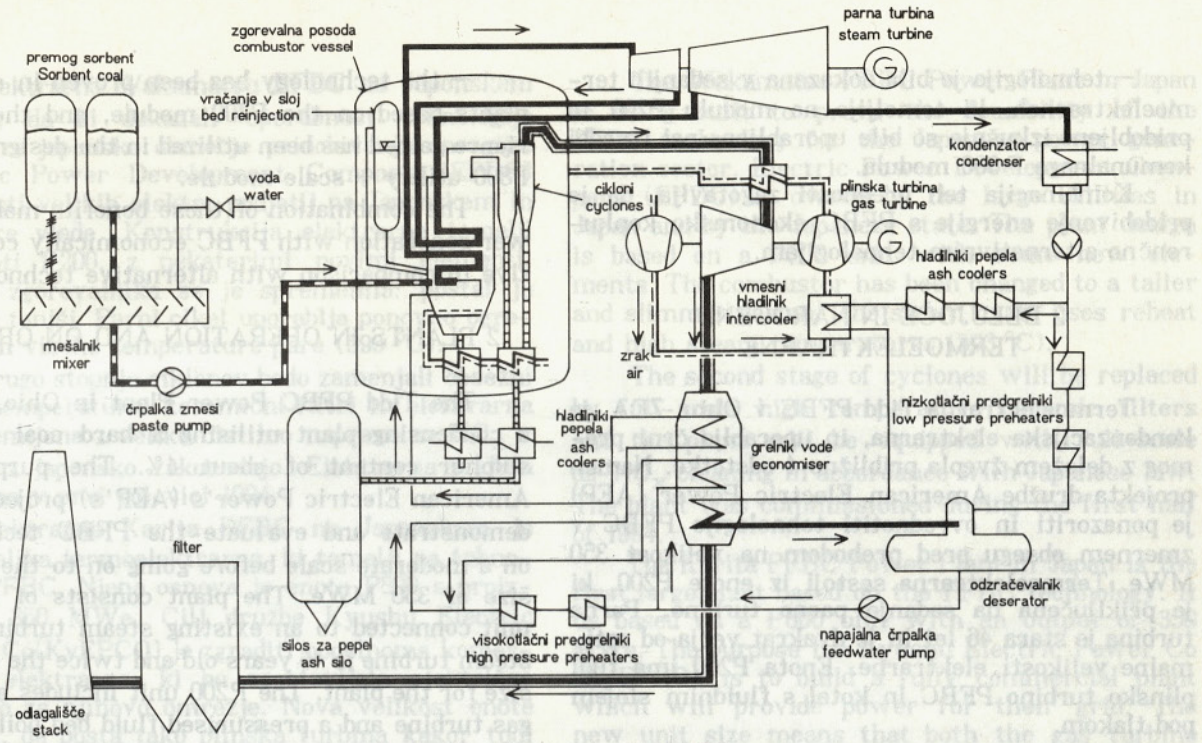
Utilities and utility organizations around the world are closely evaluating the PFBC option and are finding it highly viable, with good environmental performance, high efficiency, reliability and availability. In a recent article, EPRI concluded that PFBC should become the preferred technology for coals with sulphur levels below 4% and for repowering applications.

The market technological success of Asea Brown Boveri (ABB) PFBC plants has also encouraged other equipment suppliers to begin their development of the technology.

## 1 THE PFBC PROCESS AND EQUIPMENT

A PFBC power plant consists of three main components – a gas turbine, a steam turbine and a combustor ( fluid bed in a pressure vessel) (Fig. 1). The gas turbine provides compressed air for the fluidisation and combustion of the fuel in the fluid bed. The coal is mixed with sorbent and water to a paste, which is pumped into the fluid bed by a kind of concrete pump. Only about 0.5 % of the material in the fluid bed is actually fuel; the rest is coal ash, gypsum and sorbent. This is the bassis for the fuel flexibility of the PFBC technology and almost all coal qualities can be used in a PFBC plant.

The combustion takes place in the fluid bed at a constant and low temperature (approx. 850 °C) which is controlled by steam generating tubes immersed in the bed. The low firing temperature in a PFBC plant ensures that no thermal $NO_x$ is formed and that the $NO_x$ emissions are inherently very low. The sulphur is captured during combustion by the sorbent fed with the coal.




Sl. 1. *Kombinirani cikel PFB*
Fig. 1. *PFB Combined cycle*

Po zgorevanju v fluidnem sloju se dimni plin očisti delcev z zelo učinkovitimi cikloni in ga ekspandiramo v plinski turbini, ki poganja kompresorje in daje približno 20 odstotkov izstopne moči termoelektrarne. Grelnik vode se uporablja za to, da izloči preostalo energijo iz dimnega plina in plin ohladi na dimniku primerno temperaturo.

Pridobivanje pare poteka v ceveh, ki so potopljene v fluidni sloj. Cevi obkroža material v sloju pri temperaturi 850 °C; dobimo lahko paro pri usrezni temperaturi in jo vodimo v običajno parno turbino.

Najpomembnejše prednosti tehnologije PFBC:

– preprosta termoelektrarna, ki je prijazna tistemu, ki jo upravlja in temelji na znanih delih;

– prilagodljivost pri izbiri goriva, kjer je mogoča uporaba široke palete premoga različnih kakovosti, kakor tudi petrolejskega koksa;

– velik toplotni izkoristek za konverzijo goriva v električno energijo, ki ima za posledico majhno porabo goriva in majhne emisije ogljikovega dioksida zaradi uporabe kombiniranega cikla;

– majhne emisije $SO_x$ in $NO_x$ brez uporabe dodatne opreme, oziroma celo izredno majhne emisije ob uporabi dodatnih ukrepov, zaradi nizke zgorevalne temperature in dolgih kontaktnih časov v fluidiziranem sloju;

– kompaktnost zaradi delovanja pod tlakom, ki dopušča namestitev v razmerah omejenega prostora in olajšuje prenovo starih termoelektrarn in industrijskih lokacij;

After the fluid bed combustion, the flue gas is cleaned of particulates by high efficiency cyclones and is then expanded in a gas turbine which drives the compressors and gives about 20 % of the output from the plant. An economiser is used to extract the remaining energy from the flue gas and to cool the gas to the appropriate stack temperature.

The steam generation takes place in the tubes immersed in the fluid bed. The tubes are surrounded by bed material of 850 °C and steam of any temperature can be raised and fed to the conventional steam turbine.

The most important benefits of the PFBC technology are:

– simple and operator – friendly power plant based on well, known components;

– fuel flexibility, allowing a very wide range of coal qualities, as well as petroleum coke, to be used;

– high thermal efficiency for conversion of fuel to electricity, resulting in low fuel consuption and low carbon dioxide emissions, due to the combined-cycle arrangement;

– low emissions of $SO_x$ and $NO_x$ without the use of add – on equipment, and extremely low emissions if additional measures are applied, as a result of the low combustion temperature and the long contact times within the fluidised bed;

– compactness, due to the pressurisation, which allows installation where space is limited, and facilitates repowering of old power plants and industrial sites;

– tehnologija je bila dokazana v sedanjih termoelektrarnah, ki temeljijo na modulu P200 in pridobljene izkušnje so bile uporabljene pri izvedbi komunalnega P 800 modula.

Kombinacija teh prednosti zagotavlja, da je pridobivanje energije s PFBC ekonomsko konkurenčno alternativnim tehnologijam.

## 2 DELUJOČE IN NAROČENE TERMOELEKTRARNE

Termoelektrarna Tidd PFBC v Ohiu, ZDA, je kondenzacijska elektrarna, in uporablja črni premog z deležem žvepla približno 4 odstotke. Namen projekta družbe American Electric Power (AEP) je ponazoriti in ovrednotiti tehnologijo PFBC v zmernem obsegu pred prehodom na velikost 350 MWe. Termoelektrarna sestoji iz enote P200, ki je priključena na sedanjo parno turbino. Parna turbina je stara 46 let in je dvakrat večja od optimalne velikosti elektrarne. Enota P200 ima tudi plinsko turbino PFBC in kotel s fluidnim slojem pod tlakom.

Po drobljenju se premog meša z vodo, da nastane zmes, ki jo črpalke potiskajo v fluidni sloj. Sorbent za absorpcijo žvepla se vbrizga pnevmatično. Prvi vžig je bil novembra 1990.

Termoelektrarna Escatron PFBC v Španiji je projekt prenove elektrarne, ki uporablja staro parno turbino. Namen družbe Empresa Nacional de Electricidad S.A. (ENDESA) je predstaviti zmožnost elektrarne, da uporablja gorivo z majhno kurilno vrednostjo, preden začnejo graditi večje enote P800. Glavna sprememba v elektrarni Escatron je pri premogu. Uporabljajo črni lignit z deleži 36 odstotkov pepela, 20 odstotkov vlage in 7odstotkov žvepla. Velik delež pepela in velika količina sorbenta, ki je potrebna, da veže žveplo, sta vodili do kombiniranega sistema suhega dovajanja premoga in sorbenta. Velik pretok goriva in pepela je terjal prenovo vseh sistemov za dovajanje materiala. Število ciklonov so povečali od 7 na 9, da bi lahko obvladovali količino lebdečega pepela in tudi zmogljivost sloja za hlajenje pepela je bila povečana. Prvi vžig premoga je bil novembra 1990.

Termoelektrarna Värtan PFBC na Švedskem je nov, komercialen obrat, kombinirana termoelektrarna-toplarna (CHP) za pridobivanje toplote in elektrike velemesta Stockholm. Novi elementi v termoelektrarni Värtan so zelo stroge ekološke zahteve glede $SO_x$ in $NO_x$, dva modula P200, ki delujeta z navadno parno turbino in seveda uporaba kondenzacijske toplote. Elektrarna bo delovala le v času ogrevalne sezone od oktobra do sredine maja, saj ni namenjena delovanju brez izrabe kondenzacijske toplote. Pri Energetiki Stockholm (SE) so se odločili, da bodo uporabljali uvožen poljski premog kot primarno gorivo. Prvič so premog vžgali januarja 1990.

– the technology has been proven in existing plants based on the P200 module, and the experience gained has been utilized in the design of the P800 utility – scale module.

The combination of these benefits makes power generation with PFBC economically competitive in comparison with alternative technologies.

## 2 PLANTS IN OPERATION AND ON ORDER

The Tidd PFBC Power Plant in Ohio, US is a condensing plant utilising a hard coal with a sulphur content of about 4%. The purpose of American Electric Power's (AEP's) project is to demonstrate and evaluate the PFBC technology on a moderate scale before going on to the utility size of 350 MWe. The plant consists of a P200 unit connected to an existing steam turbine. The steam turbine is 46 years old and twice the optimal size for the plant. The P200 unit includes a PFBC gas turbine and a pressurised fluid bed boiler.

After crushing, the coal is mixed with water to a paste, which is pumped into the fluid bed. The sorbent for sulphur capture is injected pneumatically. The first firing took place in November 1990.

The Escatron PFBC Power Plant in Spain is also a repowering project using an old steam turbine. The purpose for Empresa Nacional de Electricidad S.A. (ENDESA) is to demonstrate the plant's ability to use the low - grade fuel before beginning to build large P800 units. The major difference in the Escatron Plant is the coal. The fuel used is a black lignite with 36% ash, 20% moisture and 7% sulphur. The high ash content and the high amount of sorbent required to capture the sulphur led to the choice of a combined dry feeding system for coal and sorbent. The high fuel and ash flowes required redesign of all material handling systems. The number of cyclones has been increased from 7 do 9 to cope with the volume of fly ash, and the bed ash colling capacity has also been increased. The first coal fire took place in November 1990.

The Värtan PFBC Plant in Sweden is a new, commercial Combined Heat and Power (CHP) plant producing heat and electricity for Stockholm city. The new elements in the Värtan plant are the very stringent environmental requirements for $SO_x$ and $NO_x$ two P200 modules operating with a common steam turbine and of course the cogeneration application. The plant will only operate during the heating season, from October till mid May, as it is not designed to be operated in condensing mode. Stockholm Energy (SE) have decided to use an imported Polish coal as primary fuel. Coal was fired for the first time in January 1990.

Elektrarno Wakamatsu PFBC na Japonskem gradijo, da bi dokazali uporabnost tehnologije PFBC za japonsko območje pridobivanja energije. Electric Power Development Company (EPDC) je v lasti velikih elektro podjetij na Japonskem in japonske vlade. Konstrukcija elektrarne temelji na enoti P200, z nekaterimi novimi elementi. Oblika zgorevalnika se je spremenila: postal je višji in tanjši. Parni cikel uporablja ponovno ogrevanje in visoke temperature pare (593 °C).

Drugo stopnjo ciklonov bodo zamenjali obsežni visokotemperaturni keramični filtri in elektrarna bo opremljena z veliko čistilno napravo za $NO_x$ v skladu z japonsko zakonodajo. Elektrarna je bila naročena v prvi polovici 1994.

Elektrarna Karita PFBC na Japonskem je prva velika termoelektrarna, ki temelji na tehnologiji PFBC. Njena osnova je enota P800 s proizvodnjo 350 MWe. Cilj družbe Kyushu Electric Power Co(KyEPCO) je zgraditi popolnoma komercialno elektrarno, ki bo zagotavljala električno energijo za njihovo omrežje. Nova velikost enote pomeni, da bosta tako plinska turbina kakor tudi zgorevalnik povečana. Plinska turbina je GT140P s 70 MWe in točilna parna turbina (250 bar, 566°C) je 290 MWe. Uporabljali bodo navaden trgovski premog. Načrtujejo, da bo elektrarna delovala leta 1997.

## 3 IZKUŠNJE, PRIDOBLJENE NA DELUJOČIH ELEKTRARNAH

Skupnih izkušenj polnega delovanjaPFBC je približno za 60000 ur (vključno z januarjem 1995). Število ur vsake enote je podano v preglednici 1.

Štiri elektrarne, ki že delujejo, so prve, ki uporabljajo to tehnologijo in motnja pri delovanju ene od njih včasih vodi do inšpekcijske ustavitve drugih. Kljub temu in kljub ponazoritveni naravi teh elektrarn je bilo najdaljše obdobje nepretrganega delovanja približno 1500 ur. Velik del njihovega delovanja je potekal ob delni obremenitvi, še posebej v elektrarni Värtan, kjer se potrebna proizvodnja elektrarne spreminja med dnevom in nočjo in sledi tedenskim vzorcem.

Poskusni pogon elektrarn je vključeval mnoge zagone, zaustavitve in dogodke, kar pomeni, da so lahko skrbno in obsežno raziskali polno dinamično obnašanje tehnologije PFBC.

The Wakamatsu PFBC Power Plant in Japan is being built to prove the feasibility of the PFBC technology for the Japanese power generation sector. Electric Power Development Company (EPDC) is owend by the large utilities in Japan and by the Japanese state. The plant design is based on a P200 unit with some new elements. The combustor has been changed to a taller and slimmer design. The steam cycle uses reheat and high steam temperatures (593 °C).

The second stage of cyclones will be replaced by full-scale high temperature ceramic filters and the plant will be equipped with full-scale de-$NO_x$ cleaning in accordance with Japanese law. The plant was commissioned during the first half of 1994.

The Karita PFBC Power Plant in Japan is the first large plant based on the PFBC technology. It us based on a P800 unit with an output of 350 MWe. The purpose for Kyushu Electric Power Co (KyEPCO), is to build a fully commercial plant which will provide power for their grid. The new unit size means that both the gas turbine and the combustor will be scaled up. The gas turbine is a GT140P of 70 MWe and the reheat steam turbine (250 bar, 566 °C) is 250 MWe. The design coal will be a normal trade coal. The plant is scheduled for commissioning in 1997.

## 3 EXPERIENCE FROM PLANTS IN OPERATION

The total experience from full-scale PFBC operation is about 60,000 hours (include january 1995). The number of hours for each unit is given in table 1.

The for plants in operation are the first of this technology and disturbance in one of them sometimes leads to insoection stops in the others. Despite this, and despite the demonstration nature of the plants, the longest continuous operating period is about 1500 hours. Much of the operation has been at part load, particularly in Värtan, where the required output from the plant varies between day and night and also follows weekly patterns.

The commissioning of the plants has included many starts, stop sand trips, which means that the full dynamic behaviour of the PFBC technology has been carefully and extensively proven.

Preglednica 1: *Ure delovanja posamezne enote PFBC*
Table 1: *Operational hours for each PFBC unit*

| Ure delovanja posamezne elektrarne z 95–01–31 – Hours of Operation for each plant 95–01–31 | |
|---|---|
| Elektrarna – Plant | Ure delovanja ob uporabi premoga – Hours operated on coal |
| Värtan, enota P4 – unit P4 | 11617 |
| Värtan, enota P5 – unit P5 | 15492 |
| Escatron | 17280 |
| Tidd | 12571 |
| Wakamatsu | 2998 |

Nekateri dinamični parametri so zbrani v preglednici 2. Some dynamic parameters are summarised in table 2.

Preglednica 2: *Dinamika PFBC*
Table 2: *PFBC dynamics*

| Parameter | P200 | P800 | |
|---|---|---|---|
| čas za zagon (ure) | | | start-up time (hours) |
| – hladni | 6–8 | 12–15*) | – cold |
| – topli | 2–3 | 2–3 | – warm |
| razmerje zmanjš. obr. (%) | 35**) | 35**) | turn-down ratio (%) |
| hitrost spremembe obremenitve (%/min) | 4 | 4 | load change rate (%/min) |
| čas do uporabe (ure) | <24 | <40 | access time (hours) |

*) Toplo stanje lahko vzdržujemo po zaustavitvi. – Warm conditions can be maintained after a stop.
**) Mogoče je iti celo nižje (odvisno od zahtev glede emisije in Bensonove obremenitve). – Possible to go even lower (depends on emission requirements and Benson load).

Razpoložljivost za specifične PFBC sisteme v elektrarni Värtan za ogrevalno sezono 93/94 je bila približno 92-odstotna.

Izkušnje, pridobljene iz uporabe termoelektrarn, lahko povzamemo takole:

– prenova elektrarn in novi načini uporabe,
– kombinirano pridobivanje toplote in elektrike,
– črni premog in lignit,
– dovajanje zmesi in suhega goriva,
– blok in dva kotla za eno parno turbino
– kotel z enkratnim prehodom, dogrevanje in brez dogrevanja,
– visoke temperature pare (593 °C),
– postavitev kotla na lokaciji in v delavnici,
– zmanjšanje $NO_x$ emisij, nekatalitič na in katalitič na,
– mirovanje filtra za vroči plin.

## 4 MOČ ELEKTRARNE IN UČINKOVITOST

V času preizkušanja in zgodnjega delovanja elektrarn so ugotovili številne vzroke za zmanjšanje moči elektrarn. Ti so bili:

pomanjkanje zraka zaradi:
– zahtev procesa,
– omrežnih zahtev,
– pretoka hladnega zraka v GT35P, ki je bil večji od pričakovanega,
– večjega uhajanja zraka v GT35P, kakor je bilo načrtovano,
– napačne velikosti snopov cevi,
– napačne velikosti predgrevalnika zraka na zgorele pline.

Vsako od teh pomanjkljivosti zlahka odpravimo, če lahko upravičimo stroške za to. V elektrarnah Värtan in Escatron so odpravili pomanjkanje zraka. V elektrarnah Tidd in Värtan so prilagodili površino snopa cevi. Trenutno menijo, da ni potrebno spreminjati napačno dimenzioniranih grelnikov vode v elektrarnah Escatron in Tidd.

The availability for the PFBC specific systems in Värtan during the last heating season, 93/94, was about 92 %.

The experience of power plant applications can be summarised as follows:

– repowering and new applications,
– condensing and combined heat and power,
– hard coal and lignite,
– paste and dry fuel feeding,
– blockwise and two boilers on one steam turbine,
– once – through boilers, reheat and non-reheat,
– high team temperatures (593 °C),
– site and workshop erection of boiler,
– $NO_x$ reduction, non-catalytic and catalytic,
– resting of hot gas filter.

## 4 POWER OUTPUT AND EFFICIENCY

During the commissioning and early operation of the plants a number of causes of reduced power output were identified. These were:

shortage of air due to:
– process requirements,
– system requirements,
– higher than expected cooling air flows in the GT35P,
– higher than design air leakages in the GT35P,
– wrongly sized tube bundles,
– wrongly sized economisers.

Each of these shortcomings is easily rectified if the cost can be justified. The air shortage has been corrected at Värtan and Escatron. The tube bundle surface has been adjusted at Tidd and Värtan. The wrongly sized economisers at Escatron and Tidd are not currently considered worthwhile modifyng.

Zgoraj omenjeni popravki konstrukcije se vsi nanašajo na naravo teh elektrarn, ki so bile prve tovrstne elektrarne in so bile konstruirane hkrati. S temi popravki lahko rečemo, da so izkazali obljubljene moči elektrarn in vrhunski izkoristek PFBC.

Komercialna elektrarna PFBC Värtan deluje le na način kombinirane termoelektrarne – toplarne (KTE), saj nima nizkotlačne parne turbine. Zaradi tega je neto izkoristek (neto moč + toplota, deljeno z dovedenim gorivom) elektrarne zelo velik, tj. okoli 89 odstotkov, kar je natančno toliko, kolikor so pričakovali. Proizvodnja elektrarne CHP je nižja od proizvodnje elektrarne brez izkoriščanja kondenzacijske toplote in 2 × P200 enoti v Värtan sta konstruirani za proizvodnjo 135 MWe in 224 MJ/s toplote.

Meritve, ki so jih opravili nedavno, so dokazale 142 MW električne in 234 MJ/s toplotne moči, kar precej presega načrtovane vrednosti.

## 5 UČINKOVITOST VARSTVA OKOLJA

*Žveplo*

Elektrarna Värtan ima od vseh delujočih elektrarn PFBC najstrožje zahteve za odstranitev žvepla kljub dejstvu, da uporabljajo premog z majhnim deležem žvepla. Elektrarna je bila najprej namenjena za uporabo črnega premoga z deležem žvepla 0,9%, medtem ko dejanske meritve temeljijo na uporabi premoga z deležem žvepla med 0,5 in 0,7 odstotka S. Odstranitev žvepla je bila kar 99%, z razmerjem Ca/S 2,8, kar je izredno dober rezultat, če upoštevamo majhno koncentracijo žvepla.

Elektrarna Escatron uporablja premog, ki vsebuje okoli 7% žvepla in okoli 36% pepela. Tipične vrednosti iz preglednice 3 so bile izmerjene z uporabo premoga, ki ima višjo kurilno vrednost kakor običajni premog. Dosegli so do 97-odstotno odstranitev.

Meritve, opravljene v elektrarni Tidd, so bile narejene ob uporabi premoga s 3,2% S. Zahteve v Tidd so vzdrževati stopnjo odstranitve žvepla na 90%, kar zlahka dosežemo s tehnologijo PFBC.

The above mentioned design corrections are all related to the »first of a kind« nature of these plants, which were designed simultaneously. Allowing for these corrections, it can be stated that the promised power output and superior efficiency of PFBC has been demonstrated.

The commercial Värtan PFBC plant only operates in combined heat and power (CHP) mode, as it has no low pressure steam turbine. As a consequence, the net efficiency (net power heat divided by fuel input) of the plant is very high, around 89%, which is exactly as expected. The output from a CHP plant is lower than from a condensing plant and the 2 × P200 units in Värtan are designed to give 135 MWe and 224 MJ/s heat.

The performance measurements recently carried out proved an output of 142 MWe and 234MJ/s heat, well above the design values.

## 5 ENVIRONMENTAL PERFORMANCE

*Sulphur*

The Värtan plant has the most stringent requirement on sulphur removal among the PFBC plants in operation, despite the fact that it operates with a low sulphur coal. The plant was originally designed for a 0.9% S hard coal, while the actual measurements are based on the 0.5-0.7% S coal used. The sulphur retention has been as high as 99% with a Ca/S ratio of 2.8, an extraordinarily good result considering the low sulphur concentrations.

The Escatron plant uses a coal containing around 7% sulphur and about 36% ash. The typical values in Table 3 have been measured using a coal with higher heating value than the perfomance coal. Up to 97% removal has been achieved.

The measurements in the Tidd Plant were carried out on a 3.2 % S coal. The requirement in Tidd is to keep sulphur removal at 90% and this is easily achived with the PFBC technology.

Preglednica 3: *Izkušnje z odžveplevanjem v različnih elektrarnah PFBC*
Table 3: *Desulphurisation Experience in Different PFBC Plants*

| Elektrarna – Plant | enota – unit | namenjena za – designed for | tipične vrednosti – typical values |
|---|---|---|---|
| Värtan | **mg $SO_2$/MJ** | **60** | 15 |
| | % odstranitve – removal | 92.4 | 94 |
| | Ca/S | 3.8 | 3.0 |
| Escatron | mg $SO_2$/MJ | 1200 | 600-900 |
| | **% odstranitve – removal** | **90** | 93 |
| | Ca/S | 1.8 | 2.0 |
| Tidd | lb/MMBtu | 0.5 | 0.5 |
| | **% odstranitve – removal** | **90** | 90 |
| | Ca/S | 2.0 | 1.8 |

Zahteve so prikazane kot krepko napisane vrednosti. – Requirements are shown as bold values.

*$NO_x$*

Izpuhi $NO_x$, izmerjeni v treh delujočih elektrarnah, so prikazani v preglednici 4. Zahteve elektrarnah Tidd in Escatron lahko zlahka izpolnjujejo s PFBC. Stroge zahteve v Stokholmu so vodile do razvoja in uporabe dodatnih ukrepov za zmanjšanje izpuhov.

*$NO_x$*

The emissions measured from the three plants in operation are shown in table 4. Emission requirements in Tidd and Escatron can easily be met with the levels inherent in PFBC. The stringent requirements in Stockholm have led to development and use of additional measures to reduce emissions.

Preglednica 4: *$NO_x$ izpuhi izmerjeni na elektrarni PFBC med njenim delovanjem*
Table 4: *$NO_x$ emmissions measured at PFBC Plants in operation*

| Elektrarna<br>Plant | enota<br>unit | zahteve<br>requirements | tipične vrednosti<br>typical values | posebni ukrepi<br>special measures |
|---|---|---|---|---|
| Värtan | mg/MJ | 50<br>prvotno načrtovano za 70<br>originally designed for 70 | 25 | z vbrizgom amoniaka in »minicat«<br>with ammonia injection and »minicat« or freeboard firing |
| Tidd | mg/MJ | 260 | 75 | ni – none |
| Escatron | mg/MJ | 150 | 110 | ni – none |

*Drugi izpuhi*

Izmerjeni izpuhi drugih plinov iz elektrarne Värtan so naslednji (premog z okoli 0,7 odstotkov žvepla):

CO – tipične vrednosti manj ko 5 ppm (zahteve: manj ko 200 ppm),

$N_2O$ – tipične vrednosti 20 mg/MJ (ni posebnih zahtev),

delci– tipične vrednosti okoli 2 mg/MJ z vrečastim filtrom (zahteve: manj ko 5 mg/MJ).

## 6 PERSPEKTIVE PFBC

V svetu je le nekaj možnosti za pasovno pridobivanje električne energije. Možna goriva so uran (nuklearno), naravni plin, premog in v nekaterih srečnih primerih vodni viri. Hidroenergija je možnost izbire, kjer je to izvedljivo, in število novih naročil za gradnjo elektrarn za proizvodnjo nuklearne energije je mnogo manjše kakor v sedemdesetih letih. Še mnogo desetletij bo trebą da dobijo novi viri energije, kakršna je sončna energija, večjo vlogo v proizvodnji energije. Premog s svojimi obilnimi zalogami za več ko 200 let ostaja še vedno glavno gorivo za pridobivanje energije. V večini napovedi velikosti trga za proizvodnjo energije navajajo, da bo velikost trga za pridobivanje energije iz premoga v naslednjih desetih letih izražena v moči okoli 30000 MW/leto. Postopoma bo pri tem prevladala čista premogova energija.

Jasno je, da je prihodnost čistih tehnologij za pridobivanje energije iz premoga svetla in da bo PFBC v prihajajočih destletjih vodilna tehnologija.

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*Other emissions*

The measured emissions of other gases from the Värtan Plant are as follows (coal with about 0.7 % sulphur):

CO – typical values less than 5 ppm (requirement less than 200 ppm),

$N_2O$ – typical 20 mg /MJ (no requirement),

particulates – typically around 2 mg/MJ with a baghouse filter (requirement less than 5 mg/ MJ).

## 6 PROSPECTS FOR PFBC

There are only a few options for base load power generation in the world. Possible fuels are uranium (nuclear), natural gas, coal and, in some lucky cases, hydro. Hydro power is the choice where feasible and new orders for nuclear power are much lower than in the seventies. It will take many decades for new power sources such as solar energy to become major players in power generation. Coal, with its abundant reserves for more than 200 years, will remain the major fuel for power generation. Most forecasts of the market size for power generation reach the conclusion that the coal power generation market will be about 30000 MWe/year over the next 10 years. This will gradually be dominated by Clean Coal Power.

Clearly, the future looks bright for clean coal technologies and PFBC is the leading technology for the coming decades.

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