Numerical Investigation of Power Plant Operates with Super critical Pressure Boiler

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Abstract

Numerical investigations were made of heat transfer to supercritical water flowing in a boiler vertical tube. A comprehensive set of data was obtained for pressures from 22.09 MPa to 25 MPa, mass velocity 250-400 kg/m^{2}s, the results are bulk temperatures from 345°C to 445°C, heat fluxes from 150 to 800 kW/m^2, tube diameter was 48 mm. The steady thermal model for cross section of water wall tube was established. Heat flux and temperature of working fluid are determined by using Fortran computer program at each section of the tube length. The heat transfer coefficients show behavior depending upon the heat flux. the power of plant, boiler efficiency, and plant efficiency was determined at different mass velocities, we found that the boiler and plant efficiencies increasing with the increasing of power of plant. The comparison between this investigation results and the results of other sources, we found good agreement between literatures references and numerical results of this study.

Key words: supercritical, pressure, temperature, boiler, plant, heat, flux, power.

Introduction

Supercritical fluid is a fluid at pressures and temperatures that are higher than the thermodynamic critical values (critical point). Characteristics of heat transfer and pressure drop of supercritical pressure fluids are important for the performance of Supercritical pressure high efficiency thermal power plants. It is well known that, when liquid is heated at a constant supercritical pressure, there is no phase change at a constant temperature, and there is a continuous variation from a liquid-like fluid to a vapor-like fluid. Therefore, supercritical pressure fluids in a thermodynamic equilibrium state can be regarded as single phase fluids in any conditions. The objective of this investigation is to study and analyze the performance of this type of power plants, and show the fluid flow characteristics at supercritical pressures by using Fortran computer program , finally estimate the thermal efficiency for this type of power plants and boiler efficiency. These result can be used to develop the thermal power plants and increasing the electrical power in Iraq.

Literature survey

From the literature survey, it has been found that several models have been reported with emphasis on different aspects of the boiler characteristics. Studying the response and control performance of once through supercritical (SC) units began on 1958 when work was started on a simulation of the Eddystone I unit of Philadelphia Electric Company and the work was extended for simulation of Bull run SC generation unit ([Adams 1965], [Littman 1966]). Yutaka Suzuki *et al.* modeled a once through SC boiler in order to improve the control system of an existing plant. The model was based on nonlinear partial differential equations, and the simulation results indicated that the model is valid [Shinohara 1995]. Wataro Shinohara *et al.* (1996) presented a simplified state space model for SC once through boiler-turbine and designed a nonlinear controller [Suzuki 1979]. Pressure node model description was introduced by Toshio Inoue *et al.* for power system frequency simulation studies [Lee 2007]. Intelligent techniques contributions have yielded an excellent performance for modeling. Neural network has the ability to model the SC power plant with sufficiently accurate results if they are trained with suitable data provided by operating unit [Omar 2010].

Through the 1930s and 1940s power plant operating conditions were limited to the subcritical regime because of limitations of metallurgy and water chemistry control technology. In Europe, boiler technology followed the once through philosophy. This at least in part was driven by material availability constraints and took advantage of the fact that the once through boiler generally used smaller diameter and thinner walled tubes then did the natural circulation boiler. In addition, the once through boiler eliminated the need for thick steel plate for the steam drum. In the United States where material was more readily available, the technology continued to rely on the natural circulation boiler design. In both Europe and the United States, the steam cycles used had similar steam conditions resulting in similar power generation efficiencies. For example, as early as 1941 B&W had supplied boilers to American Electric Power for operation at 16 MPa.[J.W. Smith 1998]

Before fuel can be fired in a once through boiler, a minimum fluid mass flow rate must be established within the evaporator tubes that form the furnace enclosure to protect the tubes from overheating. This minimum flow can be provided by the feed water pump or by a recirculation pump that returns the heated water back to the boiler in a closed loop for maximum heat recovery. During this start-up phase the boiler is controlled similar to a drum type unit by having in-line steam/water separators downstream of the evaporator as shown in figure (1) Separated water is drained to a water collecting vessel from which the water is pumped back to back to the economizer. To ensure that subcooled water enters the pump, a small amount of cold feed water is piped to the pump inlet line. The design includes several, depending on unit size, tangential type separators, with a single water collecting vessel.

The separator design is an optimized configuration developed to minimize pressure loss and also, vessel size. During initial firing, the inventory of water within the evaporator expands. Excess water is drained from the water collecting vessel to a flash tank to maintain an acceptable water level within the water collecting vessel. Depending on project specific requirements, the excess water may be drained directly to the condenser. [S.J. Goidich 2004]

Rankine cycle

The area under the process curve on a T-s diagram of Rankine cycle as shown in Figure (2) represents the heat transfer for internally reversible processes, we see that the area under process curve 2-3 represents the heat transferred to the water in the boiler and the area under the process curve 4-1 represents the heat rejected in the condenser. The difference between these two (the area enclosed by the cycle curve) is the net work produced during the cycle. All four components associated with the Rankine cycle (the pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes. The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and are therefore usually neglected. The boiler and the condenser do not involve any work, and the pump and the turbine are assumed to be isentropic. [Yunus 2006]

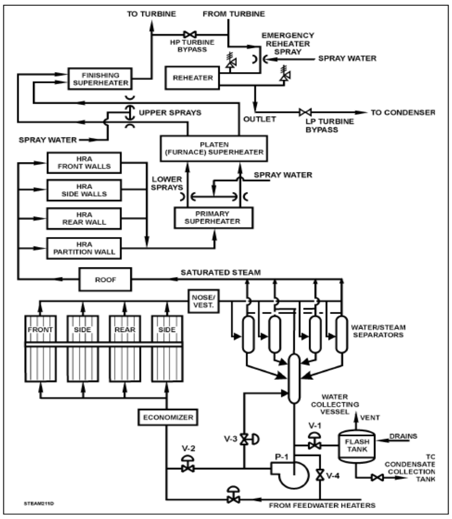


Figure (1) :water/ steam circuitry

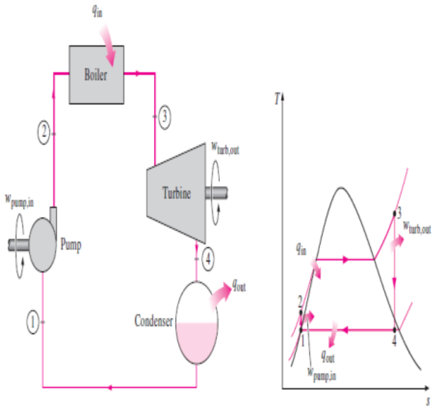
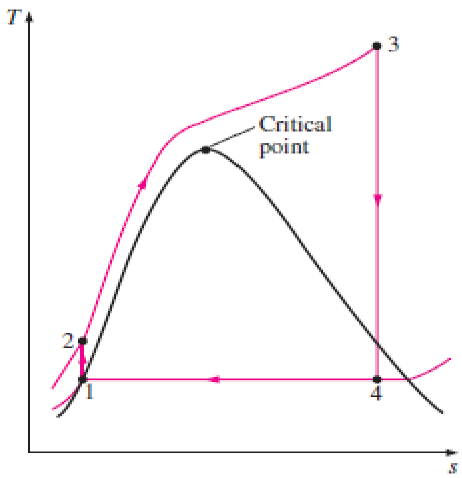


Figure (2): Simple Rankine cycle[Yunus 2006]

The *T-s* diagram of a supercritical Rankine cycle is shown in Figure(3). [Yunus 2006]



Figure(3): The *T-s* diagram of a supercritical Rankine cycle[Yunus 2006]

Mathematical model

The mathematical model consist of a circular tube This section describes the supercritical boiler model and performance parameters used in characterizing heat transfer and pressure drop. The various heat exchangers in the boiler are modeled by mass and energy balances. The sub-cooled water in the economizer is transferred directly to a supercritical steam through the water wall without passing with the evaporation status**.**

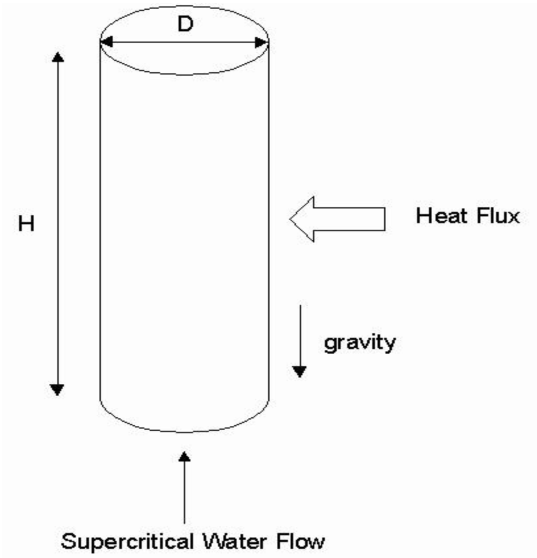


Figure (4): Mathematical model

The mass balance equation of the heat exchanger (control volume) is [Omar 2010]:

$$\frac{dm}{dt} = \dot{m}i - \dot{m}o \quad \text{….. (1)}$$

For constant effective volume, Equation (1) will be[Omar 2010]:

$$V\frac{d\rho}{dt} = \dot{m}i - \dot{m}o \quad \text{….. (2)}$$

The density is a differentiable function of two variables which can be the temperature and pressure inside the control volume, thus we have [Omar 2010]

$$V[(\frac{\partial\rho}{\partial p})_T(\frac{dp}{dt}+\frac{\partial\rho}{\partial T})_p(\frac{dT}{dt}) = \dot{m}i - \dot{m}o \quad \text{….. (3)}$$

The energy balance equation is [Omar]:

$$\frac{dU}{dt} = \dot{Q} + \dot{m}i\,hi - \dot{m}o\,ho \quad \text{….. (4)}$$

Also

$$\frac{dU}{dt} = V[h(\frac{\partial\rho}{\partial p})_T.(\frac{dp}{dt}+\frac{\partial\rho}{\partial T})_P.(\frac{dT}{dt})+\rho(\frac{\partial h}{\partial p})_T.(\frac{dp}{dt}+\frac{\partial h}{\partial T})_P.(\frac{dT}{dt})]-V(\frac{dp}{dt}) \quad \text{….. (5)}$$

Then, the energy balance equation becomes:

$$V[h(\frac{\partial\rho}{\partial p})_T.(\frac{dp}{dt}+\frac{\partial\rho}{\partial T})_P.(\frac{dT}{dt})+\rho(\frac{\partial h}{\partial p})_T.(\frac{dp}{dt}+\frac{\partial h}{\partial T})_P.(\frac{dT}{dt})]-V(\frac{dp}{dt}) = \dot{Q} + \dot{m}i\,hi - \dot{m}o\,ho \quad \text{….. (6)}$$

Solving (5) and (6) to get the pressure and temperature state derivatives.

$$\dot{P} = \frac{\dot{Q} + \dot{m}i\,hi - \dot{m}o\,ho}{\tau} \quad \text{….. (7)}$$

$$\dot{T} = Cx(\dot{m}i - \dot{m}o) - Dx.\dot{P} \quad \text{….. (8)}$$

$$hi = (hi - h - \frac{\rho(\frac{\partial h}{\partial T})_P}{(\frac{\partial\rho}{\partial T})_P}) \quad \text{….. (9)}$$

$$ho = (ho - h\,\frac{\rho(\frac{\partial h}{\partial T})_P}{(\frac{\partial\rho}{\partial T})_P}) \quad \text{….. (10)}$$

$$\tau = V[\rho(\frac{\partial h}{\partial p})_T - \frac{\rho(\frac{\partial\rho}{\partial p})_T.(\frac{\partial h}{\partial T})_p}{(\frac{\partial\rho}{\partial T})_p} - 1]/\partial t \quad \text{….. (11)}$$

$$Cx = \frac{1}{V(\frac{\partial\rho}{\partial T})_p} \quad \text{….. (12)}$$

$$Dx = \frac{(\frac{\partial\rho}{\partial p})_T}{(\frac{\partial\rho}{\partial T})_p} \quad \text{….. (13)}$$

The Reynolds number for flow in a circular tube is define as[Incropera 2006]:

$$\mathrm{Re} = \frac{\rho.Um.D}{\mu} = \frac{Um.D}{\nu} \quad \text{….. (14)}$$

Mass flow rate may be expressed as the integral form [Incropera 2006] :

$$\dot{m} = \int \rho.u(r,x)dA \quad \text{….. (15)}$$

$$Um = -\frac{r_o^2\,dp}{8\mu.dx} \quad \text{….. (16)}$$

Friction factor , which is a dimensionless parameter define as [Kays 1993]:

$$f = \frac{-(dp/dx)D}{\rho.(Um)^2/2} \quad \text{..... (17)}$$

This quantity is not to be confused with the friction coefficient, some times called the Fanning friction factor, which is defined as [Incropera 2006]:

$$Cf = \frac{\tau s}{\rho.(Um)^2/2} \quad \text{..... (18)}$$

$$\tau s = -\mu(du/dr) \quad \text{..... (19)}$$

$$Cf = \frac{f}{4} \quad \text{..... (20)}$$

For fully developed laminar flow [incropera 2006]:

$$f = \frac{64}{\text{Re}} \quad \text{..... (21)}$$

For the large Reynolds number range a correlation has been developed by Petukhov [Petukhov 1970] and is of the form:

$$f = (0.790.\ln \text{Re} - 1.64)^{-2} \text{.....} 3000 \le \text{Re} \ge 5*10^6 \quad \text{..... (22)}$$

Pressure drop can be calculated as [incropera 2006]:

$$Dp = f\,\frac{\rho.(Um)^2}{2D}\,x \quad \text{..... (23)}$$

Heat transfer calculated as [incroprea 2006]:

$$Q = \dot{m}.Cp.(To - Ti) \quad \text{..... (24)}$$

At a vicinity of the pseudocritical temperature, which is defined as the temperature with a peak of the specific heat at constant pressure .[Tohru 2003]

Nusselt number calculated from the Dittus-boelter equation [Winterton 1998] :

$$Nu = 0.023.\text{Re}^{4/5}.\text{Pr}^n \quad \text{..... (25)}$$

n=0.4 for heating, n=0.3 for cooling.

$$Nu = H.Dh/K \quad \text{..... (26)}$$

Dh= hydraulic diameter=4Ac/pw

Ac= the flow cross sectional area

Pw= the witted perimeter

Prandtl number calculated as [John H. Lenard 3rd edition 2006 h t]:

$$pr = \frac{\mu.Cp}{k} = \frac{\nu}{\alpha} \quad \text{.... (27)}$$

Thermal efficiency of power plant calculated as [Yunus 2006]:

$$\eta = \frac{wnet}{qin} \quad \text{..... (28)}$$

Boiler efficiency given as [Gill, A, power plant performance, London,1984]

$$\eta b = \frac{\dot{m}(ho - hi)}{\dot{m}f.Qhv} \quad \text{..... (29)}$$

Results and Discussion

The results of calculations shown in figures below, figure (5) shows the water steam density with bulk temperature, the density decreased with the increasing in temperature at constant pressure due to increasing in specific volume with increasing in temperature at constant pressure

The density of steam increasing with increasing in pressure due to decreasing in specific volume. One of the most important characteristics of supercritical fluids near the critical point is that their physical properties exhibit extremely rapid variations with the change of temperature, specially near the pseudocritical point (Cp =552 KJ/kg.k, T= 375 C), the temperature at which the specific heat reaches a peak for a given pressure!. This can be clearly seen from Figure (6). Figure (7) shows the thermal conductivity variation with bulk temperature at different pressures. Results clearly show the predicted overall effect of an decrease in the effective thermal conductivity with an increase in bulk temperature. Furthermore, the thermal conductivity was found to be more important at higher temperatures. Figure (8) shows the dynamic viscosity variation with bulk temperature at different pressures. As the heating increases further, the viscous effect will eventually disappear (become negligible but never zero) throughout the tube Figure (9) shows the specific enthalpy variation with bulk temperature at different pressures, the specific enthalpy increasing with increasing in bulk temperature. Figure (10) shows the Prandtl number variation with bulk temperature at different pressures, Prandtl number changes with specific heat. Figure (11) shows the variation of the heat transfer coefficient H with the specific enthalpy of steam for the tube of d=*48* mm at the mass flow rate of 50 kg/min with static pressures of 22.09 and 25 Mpa. .It is seen that at each pressure the heat transfer coefficient increased rapidly with the bulk temperature of the fluid, reached a peak value, and decreased gradually afterwards. Such a variation of the heat transfer coefficient suggests that the bulk mean temperature of the fluid has a substantial effect on the heat transfer performance near the critical point. also indicates that the peak value of the heat transfer coefficient increased as the static pressure was increased from 22.09 Mpa to 25 Mpa. . This is because the peak value of the specific heat *cp* decreases with the increase of pressure, from Fig.(11) that the heat transfer coefficient peak for each pressure occurred at a point near the corresponding pseudocritical temperature . Figure (12) shows the boiler efficiency variation with power of plant, its increased with increasing in power of plant. Figure (13) shows the plant efficiency variation power of plant. Plant efficiency increasing with increasing in the power.

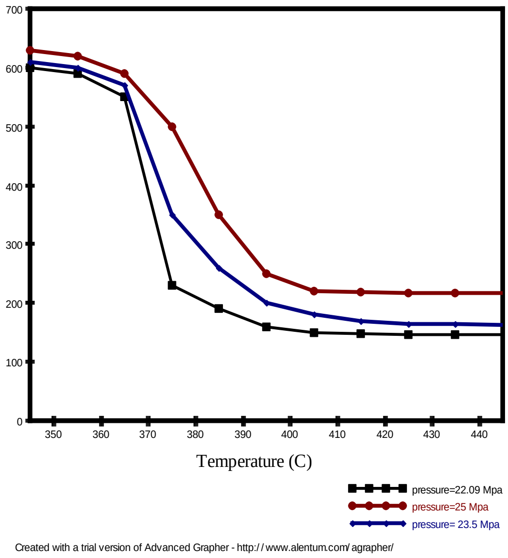


Figure (5): Density variation with bulk temperature**.**

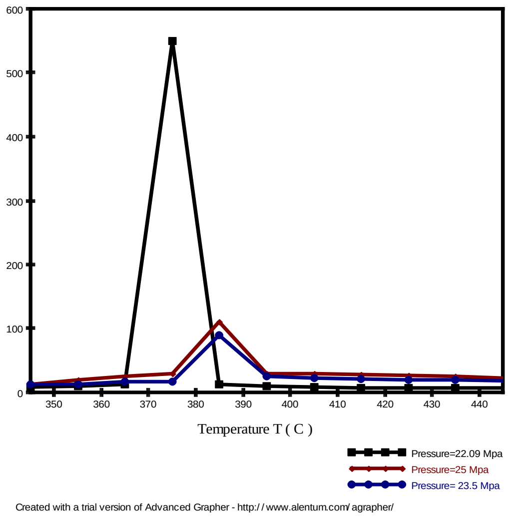


Figure (6): Specific heat variation with bulk temperature**.**

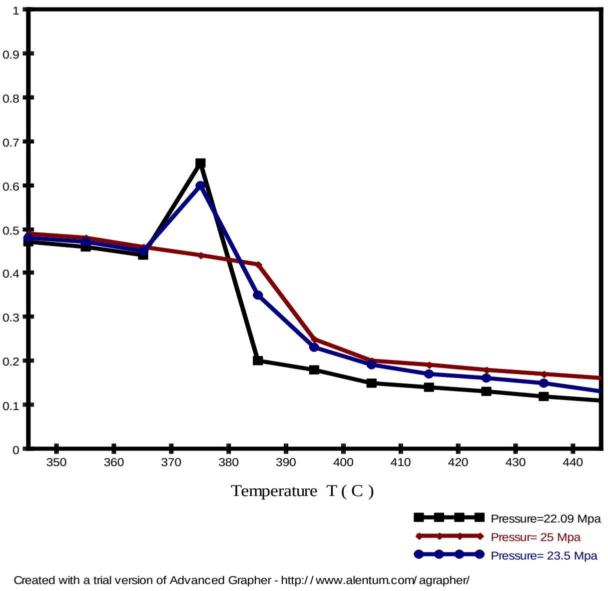


Figure (7): Thermal conductivity variation with bulk temperature

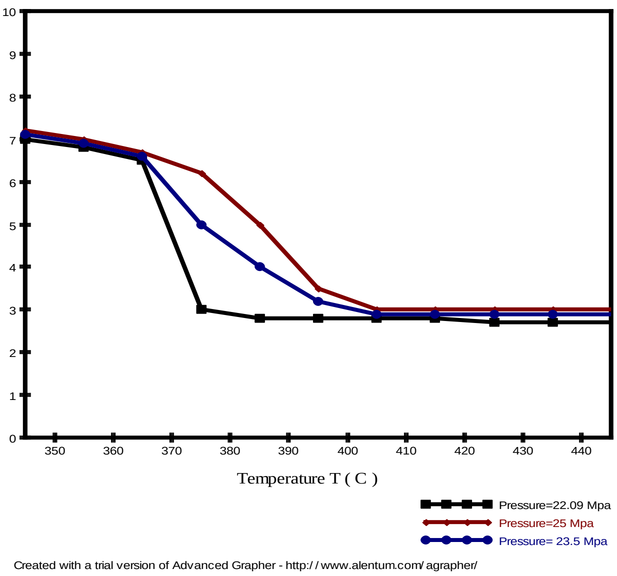


Figure (8): Dynamic viscosity variation with bulk temperature**.**

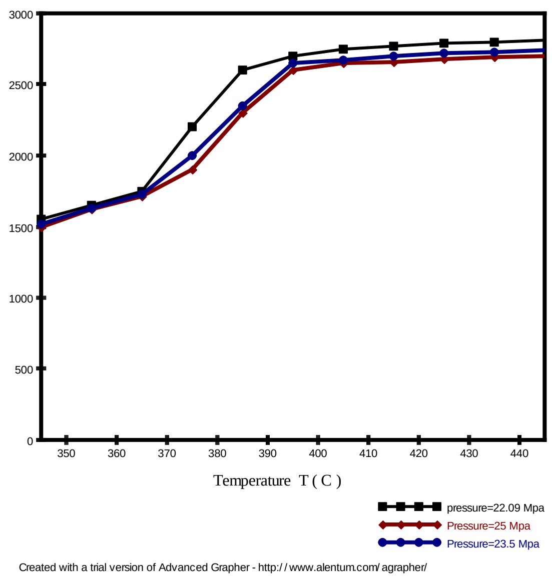


Figure (9) : Specific enthalpy variation with bulk temperature**.**

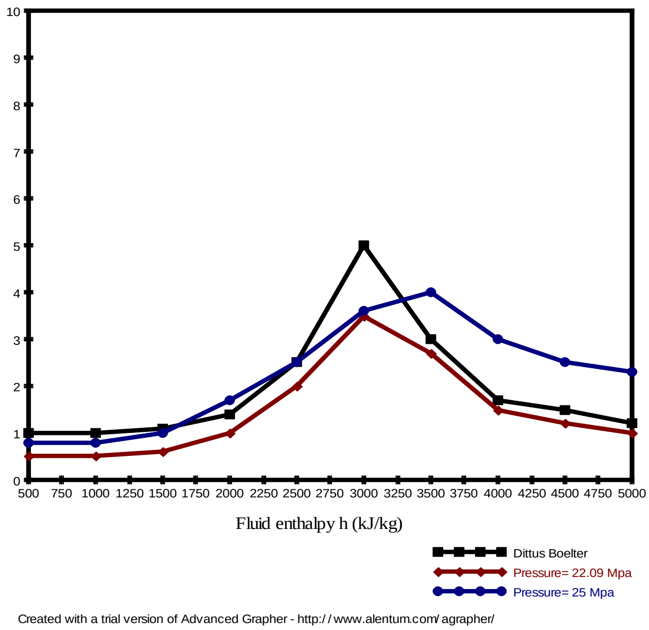


Figure (11) : Heat transfer coefficient variation with the bulk temperature.

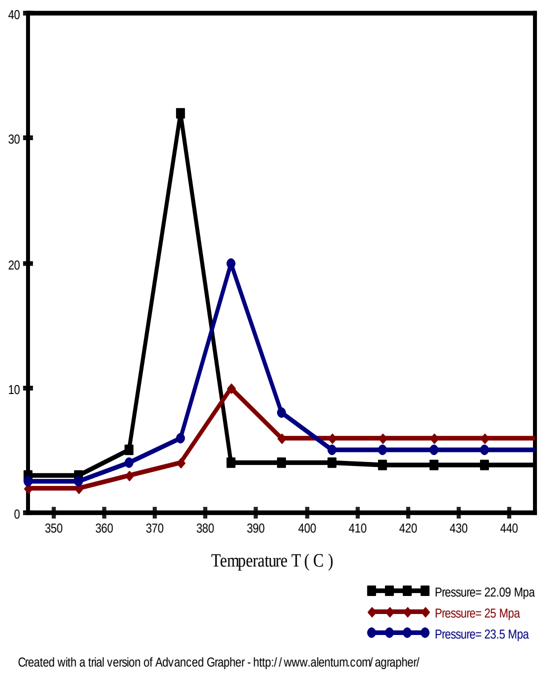


Figure (10): Prandtl number variation with bulk temperature**.**

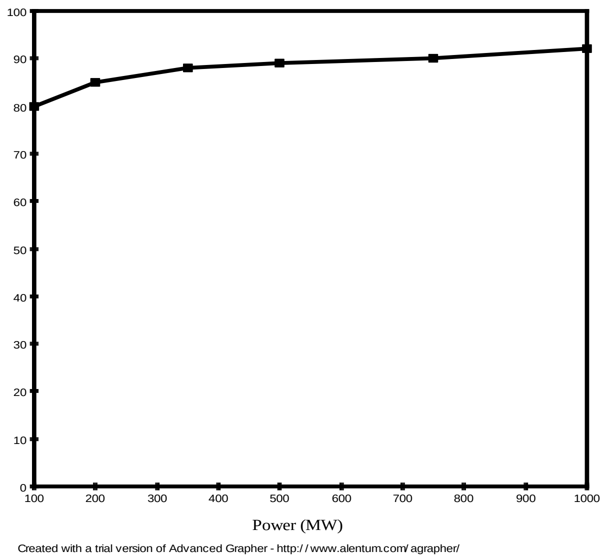


Figure (12) : Boiler efficiency variation with power of plant**.**

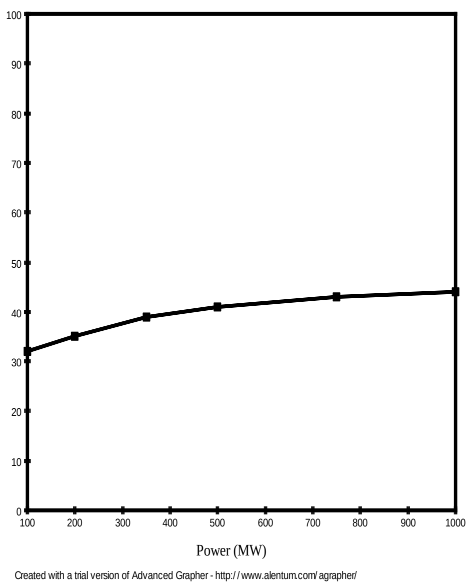


Figure (13) : Plant efficiency variation power of plant.

Conclusions

1- The heat transfer coefficients show behavior depending upon the heat flux.
2- The power of plant, boiler efficiency, and plant efficiency was determined at different mass velocities, we found that the boiler and plant efficiencies increasing with the increasing of power of plant.
3- The comparison between this investigation results and the results of other sources , we found good agreement between literatures references and numerical results of this study.

Nomenclature

A: Area (m2)
Ac: The flow cross sectional area (m2)
Cp : Specific heat at constant pressure(J/kg.k)
Cf : Fanning friction factor
Cx: Ttemperature to mass ratio (C/kg)
D: Diameter of tube (m)
Dh: Hydraulic diameter (m)
Dp: Pressure drop (N/m2)
Dx: Temperature to pressure ratio [C/(N/m2)]
f: Friction factor
G: Mass velocity (kg/s.m2)
H: Heat transfer coefficient (W/m2.k)
h: Specific enthalpy (J/kg)
ho: Outlet Specific enthalpy (J/kg)
hi: Inlet Specific enthalpy (J/kg)
K: Thermal conductivity (W/m.k)
m: Mass flow rate (kg/s)
mf: Fuel mass flow rate (kg/s)
mi: Inlet mass flow rate (kg/s)
mo: Outlet mass flow rate (kg/s)
Nu: Nusselt number
P: Pressure (N/m2)
Pr: Prandtl number
Q: Heat transfer rate (W)
Qhv: Fuel heating value (J/kg)
Qi: Input heat transfer (W)
Re: Reynolds number
T: Temperature (K)
Ti: Inlet temperature (K)
To: Outlet temperature (K)
U: Internal energy (J/kg)
Um: Velocity (m/s)
V: Volume (m3)
Wnet: Net work
μ: Dynamic viscosity (kg/m-s)
ρ: Density (kg/m3)
ν: Kinematic viscosity (m2/s)
τs : Shear stress (N/m2)
τ : Volume flow rate (m3/s)

References

1- J. Adams, D. R. Clark, J. R. Luis, and J. P. Spanbaur, “Mathematical Modelling of Once-Through Boiler Dynamics”, *IEEE Transactions on Power Apparatus and Systems*, vol 84, No. 4, Feb 1965, pp. 146-156.

2- B. Littman, and T. S. Chen, “Simulation of bull-run supercritical generation unit”. *IEEE Transactions on Power Apparatus and Systems*, vol. 85, 1966, pp.711-722.

3- W. Shinohara, and D. E. Kotischek, “A simplified model based supercritical power plant controller”. *Proceeding of the 35th IEEE conference on decision and control*, vol .4 , 1995, pp. 4486-4491.

4- Y. Suzuki and P. Sik, Y. Uchida “Simulation of oncethrough supercritical boiler”, *SIMULATION*, vol.33, 1979, pp. 181-193.

5- K. Y. Lee, J. S. Hoe, J. A. Hoffman, H. K. Sung, and H. J. Won, “Neural network based modeling of large scale power plant”. *IEEE Power Engineering Society General Meeting.* No (24-28), 2007, pp. 1- 8.

6- Omar Mohamed, Jihong Wang, Shen Guo, Bushra Al-Duri, Jianlin Wei, Modelling Study Of Supercritical Power Plant And Parameter Identification Using Genetic Algorithms Proceedings of the World Congress on Engineering 2010 Vol II, WCE 2010, June 30 - July 2, 2010, London, U.K.

7- J.W. Smith Babcock & Wilcox Barberton, Ohio, U.S.A.” Babcock & Wilcox Company Supercritical (Once Through) Boiler Technology” Published: May 1998.

8- S.J. Goidich SUPERCRITICAL BOILER OPTIONS TO MATCH FUEL COMBUSTION CHARACTERISTICS” , 2004.

9-Yunus A. Sengel,: Thermodynamics", 5th ed. 2006.

10- Incropera , "Fundamental of mass and heat transfer" sixth edition 2006

11- Kays, W. M. and M. E. Crawford. "Convective Hear and Mass Transfer, 3rd", McGraw-Hill, New York, 1993.

12- Petukhov, B. S. in T. F. Irvine and J. P. Hartnett, Eds. "Advances in Heat Transfer", Vol.6. Academic Press. New York, 1970.

13- Tohru Memoirs of the Faculty of Engineering, Kyushu University, Vol. 63, No. 4, December 2003.

14- Winterton, R. H. S., Int. J. "Heat Mass Transfer", 41, 809, 1998.

15- John H. Lenard," Heat Transfer", 3rd ed. 2006.

16- Gill, A, "power plant performance", London, 1984

دراسة عددية لمحطة قدرة تشتغل بواسطة مرجل بخاري يعمل بضغط اعلى من الضغط الحرج

كاظم فاضل ناصر

الكلية التقنية في المسيب

الخلاصة:

تم اجراء دراسة نظرية لانتقال الحرارة الى الانابيب العمودية لمرجل بخاري يعمل على ضغط اعلى من الضغط الحرج للماء. تم الحصول على مجموعة شاملة من النتائج باستخدام ضغوط تراوحت من (22.09) الى (25) ميكا باسكال وباستخدام سرع كتلية تراوحت من (250) الى (400) كغم /م2 ثا. فكانت النتائج لدرجات الحرارة العظمى للجريان تراوحت من 345 الى 445 درجة سليلوزية والفيض الحراري من(150 الى 800) كيلو واط/م2 , تم استخدام انبوب قطره(48) ملمتر, تم بناء نمودج حراري مستقر مع الزمن بمساحة مقطع لجدار الانبوب الذي يجري الماء في داخله. تم ايجاد معدل الفيض الحراري و درجة الحرارة لمائع التشغيل بواسطة استخدام برنامج الفورتران الحسابي في كل مقطع على طول الانبوب , وجد ان تصرف معامل انتقال الحرارة يعتمد على الفيض الحراري. كما تم ايجاد الكفاءة الحرارية لكل من المرجل البخاري والمحطة عند سرع كتلية لجريان المائع مختلفة فوجد ان كفاءة كل من المرجل البخاري وكفاءة المحطة تزداد بزيادة القدرة المتولده من المحطة . تم مقارنة النتائج التي تم الحصول عليها في هذه الدراسة مع النتائج الموجوده في المصادر فوجد تطابق واضح بين النتائج.