Energy Saving through Improved Boiler and Pipeline Schemes

Md. Ehsan
Professor
Department of Mechanical Engineering
Bangladesh University of Engineering and Technology
Dhaka
Email: ehsan@me.buet.ac.bd

Introduction

Steam is a widely used working fluid consumed in various engineering applications. Typically steam is used for producing mechanical work (e.g. turbine), transferring heat energy (e.g. heat exchanger) or as a raw material for chemical process (e.g. process industries, autoclave, vulcanising, food processing).

Steam is produced in boilers (steam generators), which may be of Fire-tube or Water-tube type, according to the required pressure, temperature, quality and quantity (load on boiler). Fig. 1 represents the schematic diagram of a boiler system.

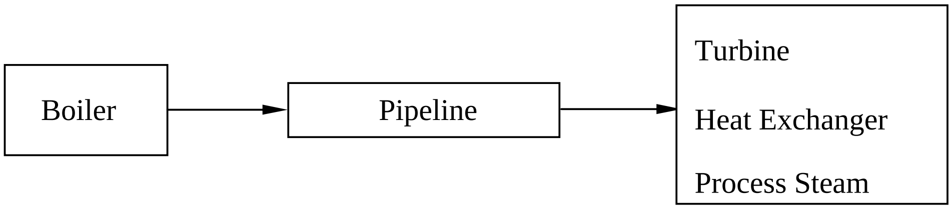


Fig. 1 A boiler system

Generally pipelines are used to transfer the steam from the boiler to the apparatus that consumes steam. Different steam consuming apparatus may be used for different applications and the physical location of the apparatus may be close or far away from the boiler.

From energy efficiency point of view, a well designed steam consumption apparatus which is a part of a thermal system can be expected to provide a good overall efficiency as long as the steam supplied to it is produced efficiently. This can be achieved by saving energy mainly if:

(i) The steam generation process in the boiler is efficient.

(ii) The steam transmission process in pipeline is efficient (ie. energy losses in the pipelines in low).

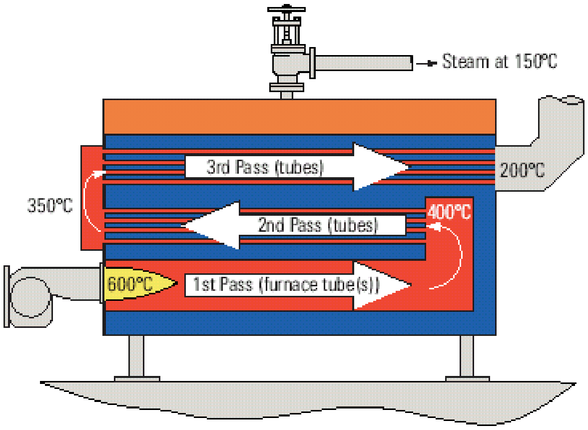


Fig 2 Typical heat path through a fire-tube shell boiler

3.2 Energy Saving through Improved Boiler Schemes

The total efficiency of the boiler can be defined as the heat energy contained in the steam produced to the heat energy available from the fuel burned.

The overall efficiency of the processes of steam generation can be high if :

(i) The combustion process of the fuel is happening efficiently

The important factors to achieve this include :

(a) Type and Quality of fuel used
(b) Type of burner used
(c) Air-Fuel ratio of combustion
(d) Technology used for controlling the combustion process
(e) Heat losses from boiler
(f) Emission of harmful gases to the atmosphere

(ii) The transfer of heat from the flue gases to water is happening efficiently

The important factors to achieve this include :

(a) Material used in construction of the heat transferring components
(b) Layout of the heat transfer surfaces – parallel/counter flow, single/multi-pass
(c) Amount of scales and films on heat exchanging surfaces
(d) Heat recovery devices used in the system – eg. economiser, air pre-heater

3.3 Boiler Efficiencies

$$\text{Boiler efficiency (\%)} = \frac{\text{Heat Exported to steam}}{\text{Heat Provided by the fuel}} \times 100$$

Heat exported to steam : depends on - temperature, pressure, quality and flow rate

Heat provided from fuel : depends on the calorific value of fuel and quality of combustion

Typical net boiler efficiencies

Type of Boiler	Net Efficiency (%)
Packaged, Three pass	87
Water Tube Boiler with Economiser	85
Economic, Two pass	78
Lancashire Boiler	65
Lancashire Boiler with Economiser	75

Courtesy : Ref. [1]

Factors Affecting Combustion Efficiency of Fuel

Type and quality of fuel used

The calorific values of different fuels are different. This may be expressed in term of Gross or Net calorific values. Most of the fuels contain hydrogen, which burns with oxygen to form water, which passes up the stack as steam. The Gross heating values of the fuels include energy used in evaporating this water. Flue gases in steam boilers plants are not condensed, therefore the actual amount of heat available to the boiler plant is reduced. The different types of fuels may need different combustion mechanisms. The air-fuel requirements may also be different. Coal as a boiler fuel tends to be restricted to specialised applications such as large water-tube boilers in power stations.

Typical Gross Heating Values of Commonly Used Fuels :

Type of Fuel	Gross Heating Value
Furnace Oil – Medium Grade-F	40 MJ/litre
Furnace Oil – Heavy, Grade-G	41 MJ/Litre
Natural Gas	38 MJ/m^3 at NTP
Propane	193 MJ/m^3 at NTP
Butane	122 MJ/m^3 at NTP

Courtesy : Ref. [1]

Type of burner used

Burners or combustion chambers are the devices responsible for :

- Proper mixing of the air and fuel in correct proportions as required, for efficient and complete combustion.
- Determining the shape and the direction of the flame.

In addition to this "**Burner Turndown Ratio**" is an important functional parameter. This is usually expressed as a ratio and is based on the maximum firing rate divided by the minimum controllable firing rate. The turndown ratio is not simply a matter of forcing different amounts of fuel through the boiler, it is increasingly important from an economic and legislative perspective that the burner provides efficient and proper combustion and satisfies increasingly stringent emission regulations over its entire operating range.

Typical Turndown Ratios available with different types of burners :

Type of Burner	Turndown Ratio
Pressure Jet	2 :1
Rotary Cap	4:1
Gas	5:1

Courtesy : Ref. [1]

Oil burners

The ability to burn fuel oil efficiently requires a high fuel surface area-to volume ratio. Oil particles typically in the range of 20 – 40 μm are most suitable for combustion. Bigger particles can not complete combustion and smaller particles pass to fast through the flame, without combustion. Atomisation of the fuel and the energy required for atomisation are main design parameters and the viscosity and variation of viscosity with temperature are very important in burner design.

Pressure Jet burner

A pressure jet burner is an orifice at the end of a pressurised tube. Typically the fuel oil pressure is in the range of 7-15 bar [1]. Varying the pressure of fuel immediately before the nozzle controls the flow rate of fuel from the burner. For variation beyond a range the orifice/nozzle size needs to be changed.

Advantages	Limitations
Relatively low cost Simple to maintain	For wide operating characteristics , boiler has to be taken off-line and nozzle needs to be changed. Orifice needs to very clean, fine mesh strainers are essential.

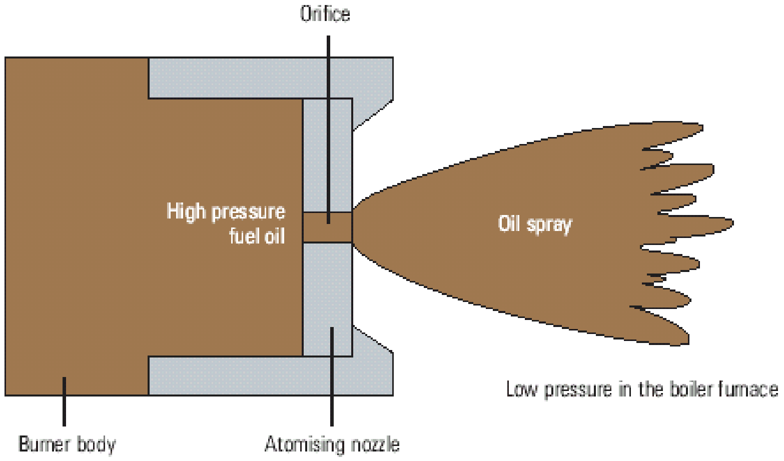


Fig. 3 Pressure jet burner

Rotary cup burner

Fuel is supplied down a central tube, and discharges onto the inside surface of a rapidly rotating cone. As the fuel oil moves along the cup the oil film gets progressively thinner as the circumference of the cap increases and eventually discharged as a fine spray from the end of the cone.

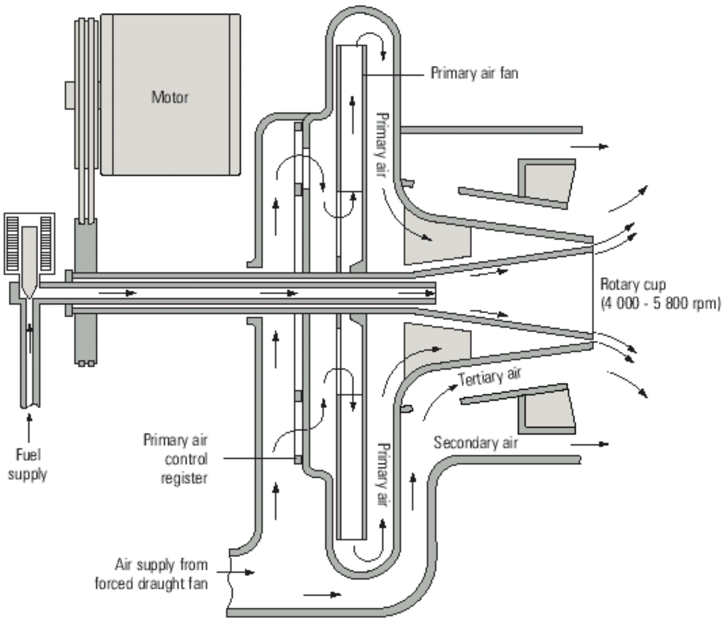


Fig. 4 Rotary cup burner

Advantages	Limitations
Robust Good Turndown ratio Viscosity is less critical	More expensive to buy and maintain

Gas burners

Using gaseous fuels, atomisation id not an issue and proper mixing of gas with the appropriate amount of air is all that is required for combustion. The burners that operate at low pressure between 2.5 – 10 mbar are called “Low pressure gas burner”. The burner is a simple venture device with gas introduced in the throat area and outside combustion air being drawn in from around. Typically the output is limited to approximately 1 MW. “High pressure gas burners”, usually operate between 12 and 175 mbar and may include a number of nozzles to produce a particular flame shape [1].

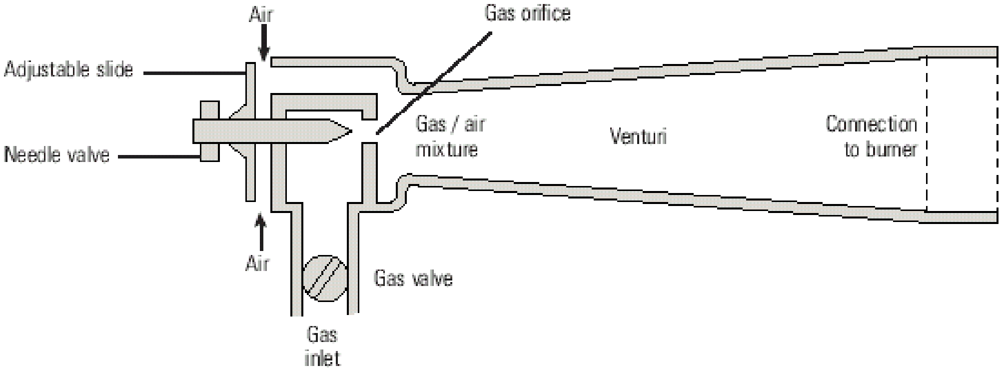


Fig 5 Low pressure gas burner

Dual-fuel burners

These burners are designed to operate with gas a the main fuel, but have an additional facility for burning fuel oil. Generally the switch over to oil fire can be carried out in a short period –involving isolation of gas supply, activation of fuel oil supply, readjustment of air-flow control and purging and re-firing of boiler.

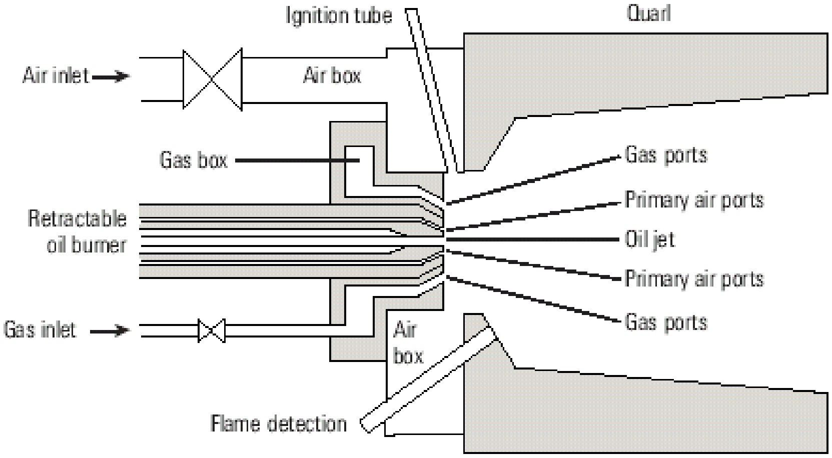


Fig. 6 Dual-fuel burners

Air-fuel ratio of combustion

Air-fuel ratio of combustion may be defines in mass basis or volume basis.

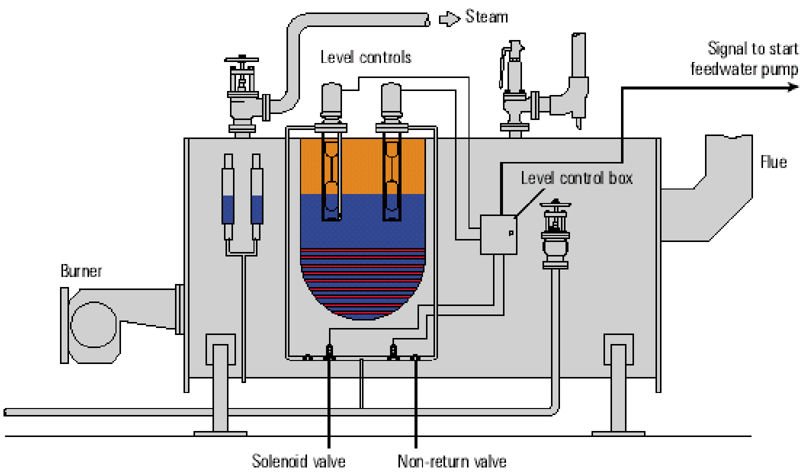
Accurate control of the amount of air with respect to the fuel flow is essential to boiler efficiency :

- Things might not be completely ideal so a chemically correct (stoichiometric) ratio may not be the best solution. Limitation of time available, non-uniformity of mixing, irregularities associated with combustion process and tendency of chemical dissociation may be dominating.
- Too much air will cool the furnace and carry away useful heat.
- Too little air and combustion will be incomplete, unburned fuel will be carried over and undesirable products of combustion (smoke) may be produced.

Typically 10-20% excess air is used in combustion processes in boiler burners to achieve satisfactory performance [5].

Technology used for controlling the combustion process

The burner, the burner control system and the water level control systems can not be viewed in isolation. All these systems should be compatible and work in a complementary manner to satisfy the steam demand of the plant in an efficient manner.



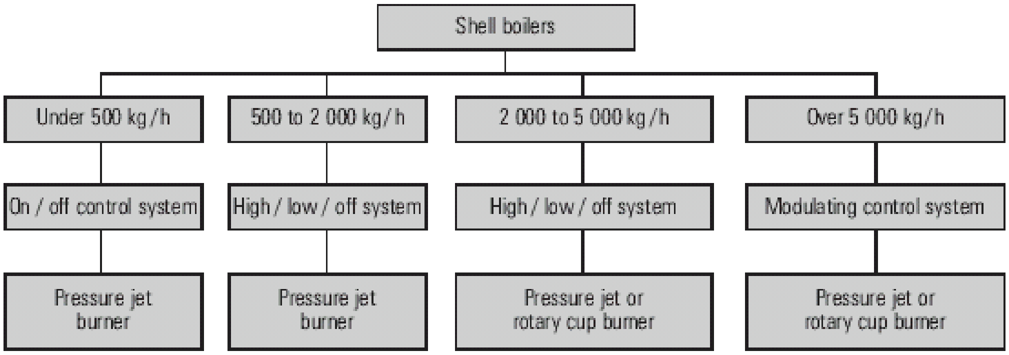


Fig. 7 Relating boiler output to controls and burner type

The most common control techniques use in boilers are [2]:

(i) ON/OFF control system (ii) HIGH/LOW/OFF control system

(iii) Modulating Control System

Type	Advantages	Limitations
ON/OFF Control System	Simple Least expensive	Subjected to large and frequent thermal shock Less precision of control Limited to small boilers Frequent purging cycles needed
HIGH/LOW/OFF Control System	Boiler is better able to response to large load variations with relatively less shock	More complex than ON/OFF control More expensive than ON/OFF control
Modulating Control System	Better response of boiler to variations in thermal load Firing rate can be modulated	Most expensive Most complex Burners with a high turndown

	without pausing for a purge cycle	capability are required

Heat losses from boiler

Heat losses from a boiler can be mainly categorised as – heat losses with the stack gas and heat loses from the boiler body structure.

Heat losses with flue gases

If enough heat from the flue gases are extracted by the boiling water, the temperature of the stack gases would be limited. If the stack gases leaving the boiler are too hot, less efficient is the boiler. The gases may be too hot if :

- The burner is producing more heat than required for a specified load on the boiler – air and fuel flow mechanisms may need calibrations.
- The heat transfer surfaces within the boiler are not functioning correctly and the heat is not being transferred to water – the heat transfer surfaces may be contaminated, and require cleaning.

The temperature of the stack gases should not be too low reaching the dew point condition. This allows formation of liquid water and some harmful acidic components which increase the potential of corrosion.

Hat losses from boiler structure

It is desired that the heat would be transmitted to the boiling water and not to the surrounding. In most modern boilers the heat-exchange section (eg. shell) is well insulated, generally with glass wool, to prevent such losses.

A reasonably well-insulated shell or eater-tube boiler of 5 MW or more capacity will typically loose between 0.3-0.5% of its energy to the surrounding. This may not appear to be a large amount, but this is actually 0.3-0.5% is of the full-load rating and this loss remains almost constant, even if the boiler is not exporting steam to the plant, and is simply on stand-by [2].

Effect on chimney/stack height on combustion

The effect of stack height on boiler performance is not a significant parameter in case of forced draft arrangement, as the manufacturer normally include the stack considerations in the boiler design. Modern control mechanism can be accommodate variations of chimney height to some extent. It is in the natural draft boilers that the stack height may effect the combustion process much more significantly. Chimney and draft performance are critical efficiency factors when burning any type of fuel in natural draft furnaces. The intensity of the draft, or difference in pressure, is usually measured in inches of water. Chimney is selected of such a height as will produce the draft required by the particular characteristics of the fuel being burned, and the amount of fuel burned by square foot of grate area. Chimneys cross-sectional area is determined as necessary to handle the gasses without undue frictional losses. Generally if the cross sectional area of the chimney is sufficiently large, the intensity of natural draft created is directly proportional to the chimney height [7]. Although the available draft may differ a little due to increased frictional losses in longer stack height. Since this is the pumping force drawing air and gaseous fuel for combustion, the chimney height needs to be well compatible with the boiler and the desired turndown ratio in natural draft boilers.

Emission of harmful gases to the atmosphere

Since 2002 there is a global commitment to a climate Change Program and 160 countries have signed to the Kyoto agreement of 1997. Two main ways of attaining the target have been identified as :

- Reduction of emission harmful gases (including CO_2) to the atmosphere
- Make quantifiable annual reductions in the fuel used.

To attain these objectives modern boilers are equipped with :

Re-circulated flue gases to ensure optimum combustion, with minimum excess air.

Greatly improved turndown ratios, which enable efficiency and emission parameters to be satisfied over a greater range of operation.

Sophisticated electronic control systems that monitor all the components of the flue gases and make adjustment to AF ratio to maintain conditions within specified parameters.

Factors Effecting Heat Transfer from Flue Gases to Steam

Material used in construction of the heat transferring components

Heat has to pass across the metallic tubes to transfer energy to water producing steam. The thermal conductivity of the metal plays an important role in the temperature of the steam produced and response of the steam generation process. A metal with poor thermal conductivity will case more temperature drop and less heat flow across, resulting in lower steam temperature and lower steam generation rate. The variation of the thermal conductivity with temperature is also of significant importance [4].

Table 1 Variation of thermal conductivity of metals with temperature

Material	Thermal conductivity (W/m°C)		
	At 25°C	At 125°C	At 225°C
Iron	80	68	60
Low carbon steel	54	51	47
Stainless steel	16	17.5	19
Tungsten	180	160	150
Platinum	70	71	72
Aluminium	250	255	250
Gold	310	312	310
Silver	420	418	415
Copper	401	400	398

The material also needs to withstand high steam pressure at elevated temperatures and resistant to the corrosive environment of steam generation as well as be economically viable for commercial production. To facilitate these requirements - boiler tubes are generally made of small diameter and used in large numbers and water treatment and pH control is done to reduce corrosion.

Layout of the heat transfer surfaces

The exchange of heat transfer between the flue gases and water may happen on a single-pass or multi-pass of the fluids in a counter-flow or parallel-flow arrangement. The tube surface temperature profiles vary as the flow is parallel or counter-flow system is used. Increasing the number of passes of the fluids increase the contact surface which increases the heat transfer rate and steam generation. However higher the number of passes more is the energy required to pass the fluid through the boiler, hence an optimisation is done. In most package boilers up to 3 passes are used to enhance heat transfer.

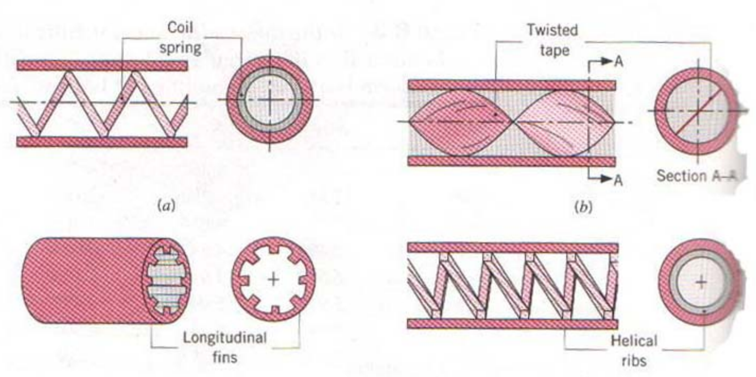


Fig. 8 Heat transfer augmentation techniques used inside fire-tubes [4]

Many modern boilers, especially fire tube package boilers use different heat transfer augmentation techniques inside the tube to increase heat transfer. Twisted tape and Wire-coil inserts are commonly used. These enhance the heat transfer from flue gas to the metal tube at a cost of more pumping energy requirement [4].

Amount of Scales and Films on Heat Exchanging Surfaces

Heat transfer across the boiler tubes is restricted by a number of thermal resistances in series. Less the amount of these resistances, more is the heat flow from flue gases and higher is the temperature of steam. The major resistance include - fluid to metal convection resistance at the flue gas side, resistance against heat conduction through metal and metal to fluid convection resistance at the steam side. The metal wall may not be the only barrier to the coductive heat transfer process. There is likely to be a film of air, condensate and scale on the steam side. On the product side there may also be baked-on product or scale, and a stagnant film of product. Agitation of the product may eliminate the effect of the stagnant film, whilst regular cleaning on the product side should reduce the scale.

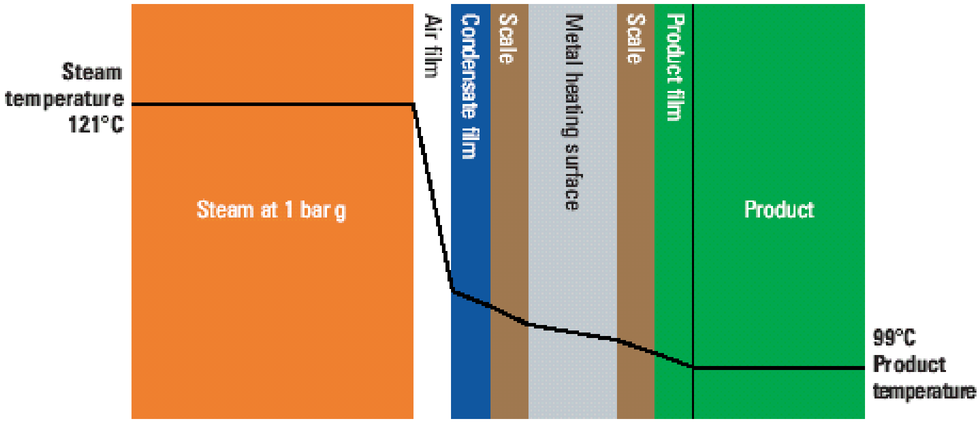


Fig. 9 Temperature gradients across a heat transfer layer of a heat-exchanger [2]

Scales form on both side of the metal tube may cause extra resistance to heat flow. The formation of such layer develops with operation and its effect of reducing the heat transfer rate is often termed as “Fouling Factor”. Use of treated water at correct physical and chemical conditions is very important to limit the extent of scale formation. This factor is considered during the boiler design to cope up with this scale formation to limited extent. Periodic cleaning of boiler tube components is generally a regular practice of boiler maintenance. Regular cleaning of the surface on the steam side may also increase the rate of heat transfer by reducing the thickness of any layer of scale, however, this may not always be possible. This layer may also be reduced by careful attention to the correct operation of the boiler, and the removal of water droplets carrying impurities from the boiler.

Formation of any air film may hamper the heat transfer characteristics significantly. As air is such a good insulator, it provides even more resistance to heat transfer. Air may be between 1 500 and 3 000 times more resistant to heat flow than steel [4].

Type of Condensation in Case of Heat Exchangers

In case of heat exchangers using the heat of steam, drop wise condensation of steam is more desirable compared to film wise condensation. If the droplets of water on the heat transfer surface do not merge immediately and no continuous condensate film is formed, ‘dropwise’ condensation occurs. As a larger proportion of the heat transfer surface is exposed, heat transfer rates which can be achieved during dropwise condensation, are generally much higher than those achieved during film wise condensation.

In the design of heat exchangers where dropwise condensation is promoted, the thermal resistance it produces is often negligible in comparison to other heat transfer barriers. However, maintaining the appropriate conditions for dropwise condensation have proved to be very difficult to achieve. If the surface is coated with a substance that inhibits wetting, it may be possible to maintain dropwise condensation for a period of time. For this purpose, a range of surface coatings such as Silicones, PTFE and an assortment of waxes and fatty acids are sometimes applied to surfaces in a heat exchanger on which condensation is to be promoted. However, these coatings will gradually lose their effectiveness due to processes such as oxidation or fouling, and film condensation will eventually predominate [2].

Heat Recovery Devices used in the System

Modern boilers use special accessories like air preheater and economiser to recover heat from the stack flue gases. Air preheater heat-exchanger recovers heat from the stack gas by heating the in coming air before entering to the burner. Economiser is used to preheat the pressurised feed water before entering the boiler by recoving heat from the exhaust flue gases. Addition of such systems increase the installation cost but improve the fuel consumption and efficiency.

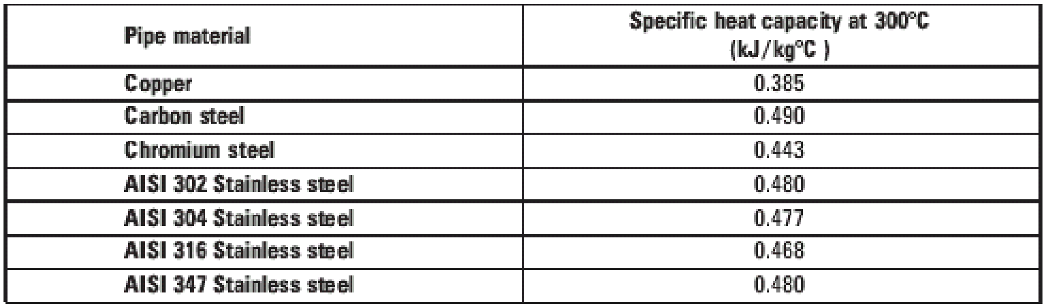
Energy Saving through Improved Pipeline Schemes

Much attention has been devoted to energy conservation of steam generators (boilers) and process equipment (heat exchangers, dryers, evaporators etc). However a large quantity of energy lost in transporting steam from boilers to different areas of the plant. Large chemical plants like fertilizers, petrochemicals, refineries etc. have kilometers of steam network which could be major energy guzzlers if proper attention is not given to this area. Reducing energy losses in the distribution or transmission system also helps in improving the ‘end-use’ efficiency. Followings are main areas of energy conservation to steam lines [6].

The Material used for piping and insulation

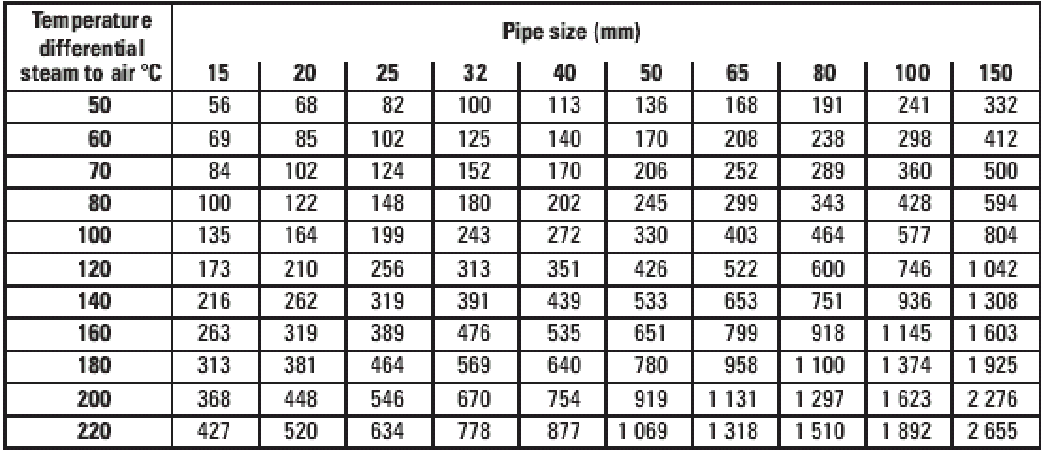
Steam will condense and give up its enthalpy of evaporation on the walls of any pipe or tube exposed to ambient air. In some cases, such as ‘Steam Mains’, heat transfer is minimised by the lagging of the pipes, using thermal insulation around it. The pipe material used is very important in case steam running without insulation controlling the heat losses and the warm-up period for their different dimensions and specific heats.

Table 2 Typical Specific Heats of Metal Pipes [4]



Pipe material	Specific heat capacity at 300°C (kJ/kg°C)
Copper	0.385
Carbon steel	0.490
Chromium steel	0.443
AISI 302 Stainless steel	0.480
AISI 304 Stainless steel	0.477
AISI 316 Stainless steel	0.468
AISI 347 Stainless steel	0.480

Table 3 Heat losses (W/m) from unlagged steel pipes freely exposed in air at 20°C [2]



Temperature differential steam to air °C	Pipe size (mm)									
	15	20	25	32	40	50	65	80	100	150
50	56	68	82	100	113	136	168	191	241	332
60	69	85	102	125	140	170	208	238	298	412
70	84	102	124	152	170	206	252	289	360	500
80	100	122	148	180	202	245	299	343	428	594
100	135	164	199	243	272	330	403	464	577	804
120	173	210	256	313	351	426	522	600	746	1 042
140	216	262	319	391	439	533	653	751	936	1 308
160	263	319	389	476	535	651	799	918	1 145	1 603
180	313	381	464	569	640	780	958	1 100	1 374	1 925
200	368	448	546	670	754	919	1 131	1 297	1 623	2 276
220	427	520	634	778	877	1 069	1 318	1 510	1 892	2 655

As an insulating material the use of asbestor is on the decline due to health hazards associated with it. A number of insulating materials are used more commonly now a days. Some their insulating properties are given below :

Table 4 Properties of Insulation Materials [4]

Material	Density (kg/m^3)	Thermal Conductivity at 300K (W/m.K)
Glass fibre, paper faced	28	0.038
Glass fibre, coated duct liner	32	0.038
Glass fibre poured or blown	16	0.043
Aluminium foil separating fluffy glass mat.	40	0.00016

Insulating Cement, with setting binder	560	0.108
Asbestor paper, laminated and corrugated 4-ply 6-ply 8-ply	 190 255 300	 0.078 0.071 0.068

Critical thickness of Insulation

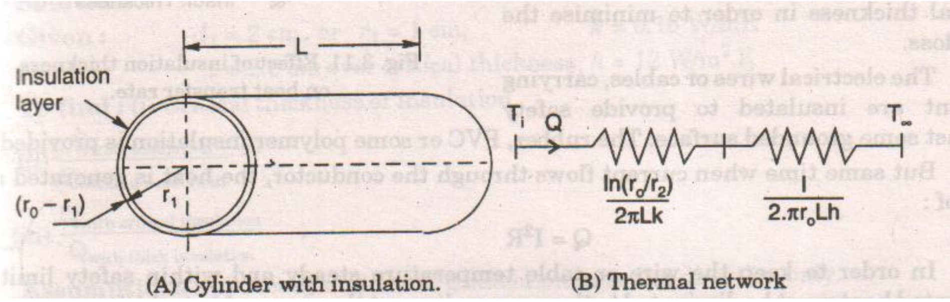


Fig. 10 Critical thickness of insulation Courtesy [4]

It should be noted that while designing insulation thickness on metallic steam pipes, the phenomenon of critical thickness of insulation should be kept in consideration. Critical thickness can be calculated from the ratio thermal conductivity of insulation to the convective heat transfer coefficient on the exposed side (r_{cr} = k/h). If the outer radius of the insulation is less than the critical thickness, the resistance decreases and the heat losses increase if the insulation thickness is increased. On the other hand if the insulation thickness is greater than the critical value, then the resistance increases and the heat losses decrease if the insulation thickness is increased further. The insulation thickness on steam/heat pipes are always kept more than the critical thickness to minimise the heat losses.

Table 4 Typical heat losses from insulated pipes (W/m) [2]

Process diameter (mm)	Insulation thickness	Product/ambient temperature difference (°C)						
		25	75	100	125	150	175	200
DN100	50	14	43	58	71	86	100	115
	100	9	26	36	45	54	62	71
DN150	50	20	59	77	97	116	136	155
	100	12	35	46	58	69	81	92
DN200	50	24	72	97	120	144	168	192
	100	14	41	55	70	84	98	112
DN250	50	29	87	116	145	174	202	231
	100	16	49	66	82	99	115	131

Heat losses from steam condensation

The rate of condensation will be at its highest during the warming up period, and it is this that should govern the size of steam traps used for mains drainage. With the steam main in use, there will also be a smaller (but continual) heat loss from the pipe. Both of these components can be calculated as the 'warming up load' and the 'running load'.

Warm-up load heating will initially be required to bring the cold pipe up to working temperature. It is good practice to do this slowly for safety reasons, the pipes also benefit from reduced thermal and mechanical stress. This will result in fewer leaks, lower maintenance costs, and a longer life for the pipe. Slow warm-up can be achieved by fitting a small valve in parallel with the main isolating valve. The valve can be sized depending on the warm-up time required. Automating the warm-up valve to open slowly on large pipes can improve safety. The time taken to warm up any steam main should be as long as possible within acceptable limits to minimise mechanical pipe work stress, optimise safety and reduce start-up loads.

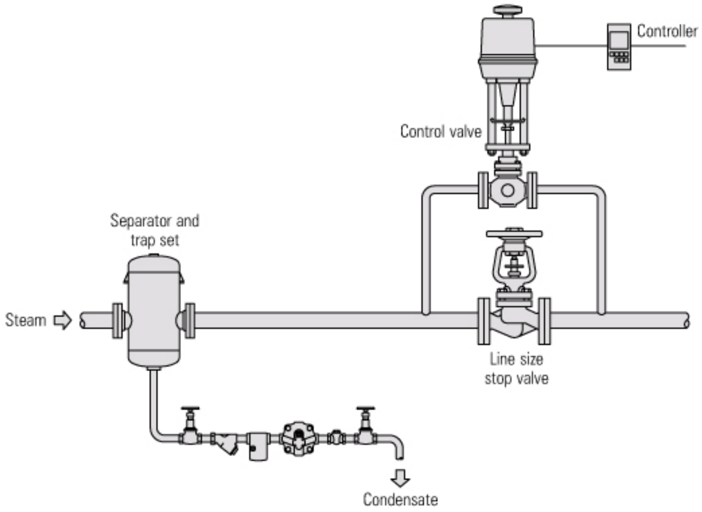


Fig. 11 Automatic warm up valve in a bypass, Courtesy : Ref. [2]

Heat loss to the surroundings occurs as steam is distributed through long distances of pipe work, through machinery and fittings etc. despite lagging and insulation that is designed to minimise the heat loss. As the temperature falls steam can be condensed to form hot liquid condensate. This referred as the steam consumption of the pipeline. The amount of condensate formation can be estimated from the heat losses from the pipings. Hot condensate is a valuable resource and its collection and return to the steam raising system minimises the quantity of fresh water and energy required for steam raising at the boilers. It is therefore preferable but not always possible to capture and return condensate by means of a condensate return system. Where it is not possible to capture the condensate this is generally released directly to ground.

Heat losses at valves and fittings

Steam system pipework is protected by a number of different systems. Safety relief valves are installed along lengths of steam main in order to relieve overpressure of steam in the line and hence protect the steam main from catastrophic failure should the steam supply pressure rise. Safety valves for steam are generally designed and sized to relieve steam but not condensate. The presence of safety relief valves on steam systems relieving to atmosphere is clearly visible due to white plumes of steam that are present. Following a steam release to reduce the pressure the safety valves normally re-seat. Safety valves are designed to relieve the pressure allowing for a maximum rate of steam release. The capacity of a safety relief valve to relieve hot liquid condensate is less than that for steam due to the different characteristics of gases and liquids. Safety relief valves are not designed to vent condensate and under these circumstances can not be guaranteed to provide adequate pressure relief for the pipe work system concerned.

The hot liquid condensate must be removed from the steam mains in order to prevent flooding of the pipework and the carryover of liquid into instruments, machines and process areas. An extreme condition known as water hammer results in slugs of liquid being conveyed at high velocity through the steam main pipework carried by the steam. The liquid impacts on valves, bends and instrumentation and can cause sudden and catastrophic damage. Removal of condensate is achieved by the installation of steam traps which are designed to capture and then release the condensate from the steam main in a controlled manner. Detailed calculations must be carried out on steam main layouts to correctly size steam traps and safety valves for condensate removal and pressure relief.

Although it could be useful for reducing heat losses, conveying liquids at high speeds in gas pipelines is undesirable due to the considerable damage that can be caused by the impact of the liquid on fittings such as instruments, valves and bends. Every additional valve and fitting creates an additional source of heat loss.

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