Algorithm Document for Process Heating Assessment & Survey Tool - Excel Version (PHASTEx)



Arvind Thekdi

Sachin Nimbalkar

Kiran Thirumaran

November 1, 2016

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Energy and Transportation Science Division

Algorithm Document for Process Heating Assessment & Survey Tool - Excel Version (PHASTEx)

Arvind Thekdi (E3M Inc.)

Sachin Nimbalkar (Oak Ridge National Laboratory)

Kiran Thirumaran (Oak Ridge National Laboratory)

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ACRONYMS

PHAST Process Heating Assessment and Survey Tool

PHASTEx Process Heating Assessment and Survey Tool Excel

ORNL Oak Ridge National Laboratory

UNITS OF MEASURE

Btu British Thermal Unit

MMBtu Million British Thermal Unit

kCal Kilo Calorie

F Fahrenheit

lb pound

kg kilogram

h hour

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# OVERVIEW

This document lists the inputs and calculation methodology used for the PHASTEx tool. It includes the constants and equations, which will be used to produce the necessary outputs. The intent of this document is to serve as guidance to the developers for PHASTEx on the inputs to collect and calculate energy use or loss in several areas of heating equipment, referred to as a furnace for simplicity in this document, and to prepare a heat balance for current operating conditions and modified conditions. The modified conditions can be developed using suggested energy savings measures for each area of the furnace. This document is prepared by a compilation of calculation methodologies described by several contributors.

# WHAT IS PHASTEx?

## INTRODUCTION

A large percentage of total energy consumed in an industrial plant is used for process heating equipment such as furnaces, heaters, ovens, kilns, and boilers. This equipment uses a variety of fuels to supply heat required to raise temperatures of or induce phase change (melting, vaporizing) in a variety of materials. It is possible to reduce the energy use of process heating equipment by conducting an energy audit or assessment that identifies areas of energy use or losses and take actions to reduce these losses, resulting in a reduction in overall energy use.

The Process Heating Assessment and Survey Tool, commonly known as PHAST, was developed to conduct an energy assessment or audit of the heating equipment used by many industries. The tool has been used in several industrial plants in a number of countries to identify energy use distribution and analysis to identify and estimate energy losses, as well as to analyze potential energy savings by applying commonly recommended energy savings measures. The Excel version of PHAST, known as PHASTEx, is specifically designed to enhance the capabilities of PHAST. It can be used where it is necessary to consider multicomponent charge-loads and account for a number of different sections for various areas of energy loss.

PHASTEx can be used to estimate potential energy savings with application of energy saving measures, which are listed as an appendix to the PHASTEx tool and discussed in process heating training workshops. The results of potential energy savings with application of energy saving measures are displayed under a separate column, “modified conditions.”

## DATA COLLECTION AND USE OF PHASTEX

Use of PHASTEx requires the collection of certain critical data for the heating equipment. The required data are collected when the heating equipment is operating at typical or average production conditions. The type of data and where it is collected depend on the design and operation of the heating system. Required data can be collected by the plant personnel or an outside consulting organization. The data collection process in most cases does not disturb production. However, it may be necessary to install or use process monitoring instruments at selected areas of the heating system. It is also necessary to collect information on the products and fuel used for the equipment. In most cases, such data are easily available from the plant personnel, installed data collection equipment, or records.

Possible areas where data collection may be required are listed below.

* Plant General Information
* Furnace Data
* Charge material – solids (wet or dry)
* Charge material – liquids
* Charge material – gases/vapors
* Fixtures, trays, conveyor, etc.
* Wall surface heat losses
* Water or air cooling (internal)
* Atmosphere or makeup air
* Flue gases
* Radiation losses from openings
* Power use by electric motors and other devices
* Other heat loss or generation

PHASTEx consists of several calculators to enter required data, perform appropriate calculations, and prepare reports as mentioned earlier. PHASTEx also includes suggestions for possible energy-saving measures for the areas of energy use.

## RESULTS OF PHAST ANALYSIS

A number of reports are generated to show various areas of energy use or losses and the amount of energy used for each of these areas. Information contained in a report for the current energy use is used to identify areas of energy losses or inefficient use of energy and to make decisions on action items or suggested energy saving measures. The second section of the report shows similar information after entering “modified” operating conditions which are expected to exist after implantation of certain practical energy saving measures selected by the user. A third report shows comparison of performance in the form of a bar chart and Sankey Diagram. The results show heat balance for the system in several units such Btu/h, kCal/h, and MMBtu/h. The heat balance is for current operating conditions and expected operating conditions after implementation of the selected energy saving measures.

Figure 1 illustrates an example of a heat balance or distribution of heat developed by using operating data when the heating equipment is operated under current conditions. A similar pie chart is prepared for modified conditions.

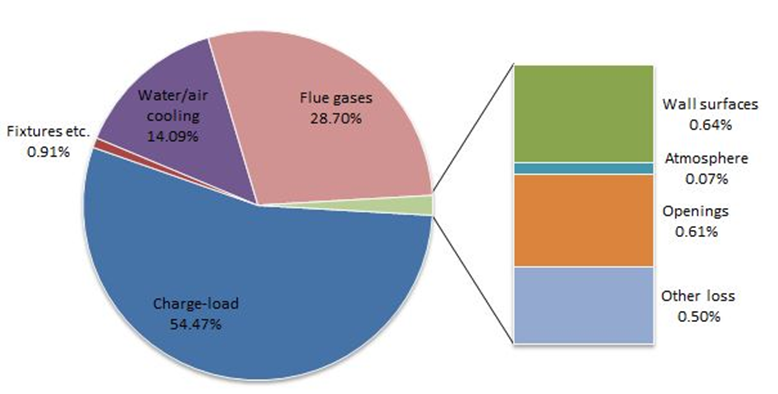


Figure 1. Typical heat distribution results for current operating conditions using PHASTEx.

The report also gives a bar chart for comparison of energy use in various areas under current and modified operating conditions. Figure 2 shows such a chart.

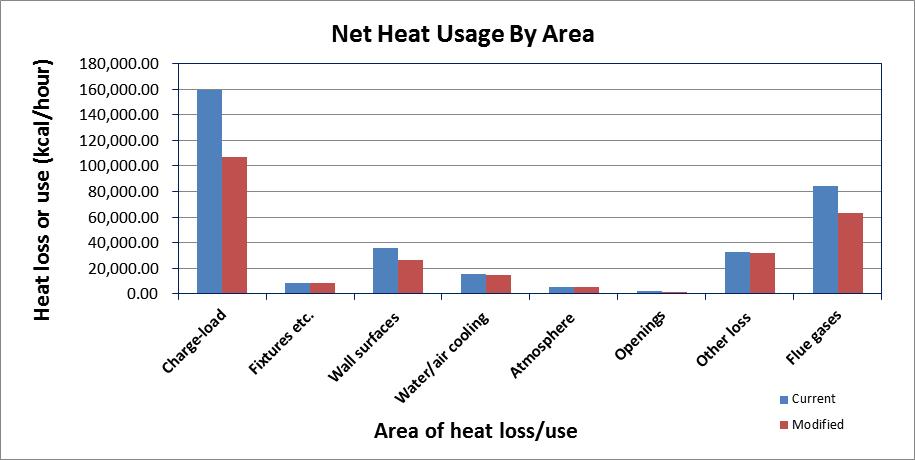


Figure 2. Comparison of energy use with current and modified conditions.

The results are also displayed, as shown in Figure 3, in the form of a “static” Sankey Diagram to visualize various losses and use of energy.

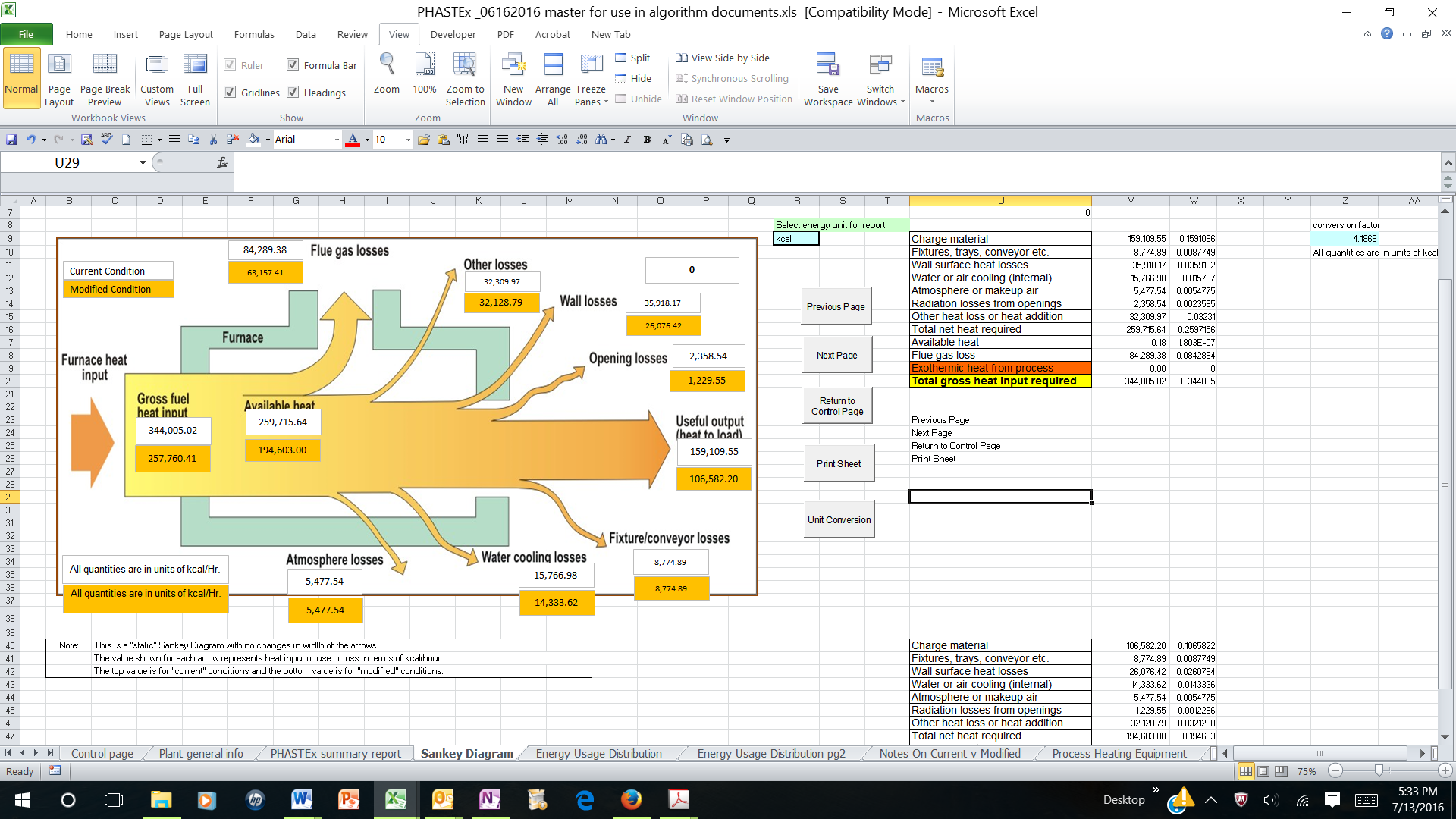


Figure 3. Static Sankey diagram with energy use distribution or heat balance for the furnace under current and modified conditions.

Information given in these reports can be used for comparison of performance of similar equipment at the same location or other plant locations, and to enable one to take appropriate actions to minimize heat losses resulting in improved performance and energy savings.

# PHASTEx COMPONENTS/CALCULATORS OVERVIEW

PHASTEx consists of several calculators to enter required data, perform appropriate calculations and prepare heat balance reports. Each calculator is designed to estimate heat loss or heat use for process heating equipment under current operating condition and “modified” conditions where changes are made to operating parameters to reduce energy use. This information is used to prepare a heat balance expressed in various forms (i.e., pie charts, bar charts, Sankey diagrams, and tables). Heat balance is shown for current operating conditions and expected operations (modified condition) after application of selected energy savings measures. PHASTEx also includes suggestions for possible energy saving measures for the areas of energy use. The PHASTEx report also includes a list of selected energy saving measures and energy savings due to application of the modifications for each area in the heating system.

Areas of energy use within a typical heating system for which calculators are developed are listed below.

* Charge material – solids (wet or dry)
* Charge material – liquids
* Charge material – gases/vapors
* Fixtures, trays, conveyors, etc.
* Wall surface heat losses
* Water or air cooling (internal)
* Atmosphere or makeup air
* Flue gases
* Radiation losses from openings
* Power use by electric motors and other devices
* Other heat loss or generation

## RESULTS OF PHAST ANALYSIS

As mentioned in the previous section, a number of reports are generated to show various areas of energy use or losses and the amount of energy used for each of these areas. Information contained in a report for the current energy use is used to identify areas of energy losses or inefficient use of energy and to make decisions on action items or suggested energy saving measures. The second section of the report shows similar information after entering “modified” operating conditions which are expected to exist after possible implantation of certain practical energy saving measures. A third report shows comparison of performance in the form of a bar chart and Sankey diagram. The results show heat balance for the system in several units such a Btu/h, kCal/h, and MMBtu/h. The heat balance is for current operating conditions and expected operating conditions after implementation of the possible and analyzed energy saving measures. Additional details on the report are given in a later section in this document.

This document describes inputs and calculation methodology for each of these calculators with additional calculations of total input requirements for current and modified conditions.

## LOAD/CHARGE MATERIAL

###### Description

This section calculates the heating energy required to increase the temperature of the material composition (often referred to as a load or a charge) from the initial inlet and to final out conditions. Heating of the material may result in phase change for the material. During the heating process, inlet and outlet compositions may also vary, a heat of reaction value may be added or subtracted, and there may be other heat addition or subtraction for special cases such as heat of phase change. The reaction can be exothermic (production of heat) or endothermic (absorption of heat) during the heating process. It may also be necessary for special situations to add or subtract additional heat requirements for the total requirement calculations.

PHASTEx allows for selection of three types of materials: solid with moisture content, liquid, and gas with vapor content. The following sections give details of the required input data, calculation methodology with equations used, and results for charge materials in the form of solids, liquids and gases.

###### Solid Material Inputs and Results (for each material)

The following table gives a list of input parameters, units, and symbols used for examples of calculations for solids materials. PHASTEx allows use of up to three solid materials, and it is necessary to give input information for each of the materials used.

Table 1. Input Parameters - Solid Material

|  |  |  |
| --- | --- | --- |
| **Input Parameter – Solid Material** | | |
| **Process Parameters** | **Units** | **Symbol** |
| Average specific heat of the solid material (dry) | Btu/(lb-°F) |  |
| Latent heat of fusion | Btu/lb |  |
| Specific heat of liquid from molten material | Btu/(lb-°F) |  |
| Melting point | °F |  |
| Charge (wet)-feed rate | lb/h |  |
| Water content as charged (%) | % |  |
| Water content as discharged (%) | % |  |
| Initial temperature | °F |  |
| Charge material discharge temperature | °F |  |
| Water vapor discharge temperature | °F |  |
| Charge melted (% of dry charge) | % |  |
| Charge Reacted (% of dry charge) | % |  |
| Heat of reaction | Btu/lb |  |
| Endothermic/exothermic | - |  |
| Additional heat required | Btu/h |  |

Note: Thermal properties (top four items) are given when the material is selected from the database. If not, the user is required to give the required data.

Table 2. Output Results – Solid Material

|  |  |  |
| --- | --- | --- |
| **Calculation Result** | **Units** | **Symbol** |
| Total heat for charge material - solids | Btu/h |  |

###### Constants

This calculator uses thermal and physical properties of the charge material. The properties include specific heat of solid, liquid or gas/vapor phase of the materials, density, melting or other phase change temperature, heat of phase change, and heat of reaction if associated with the heating process. Much of this information can be obtained from literature or references listed at the end of this section or from in‑house knowledge and databases developed by the user. Boiling point of moisture is 212 °F, and specific heat of water vapor is 0.481 Btu/lb·°F. for commonly used industrial process heating equipment.These are average values used in calculations.

###### Equations/Calculations

Total Energy Use = [sum of energy use for various components of the charge materials].

###### Input – Solid Material

It is possible to select three different materials as input for the charge/load material. This option allows heat requirement calculations when the feed material includes several components. For example, melting of glass requires a mixture of sand, recycled glass, and other additives. In this case, it is possible to calculate the total heat requirements by making calculations for three different materials that combine into one component (glass, in this case) as output of the process. The following calculation method is used for each component.

###### Heat Requirement calculation equations

Solid calculations for heating solid material as charge or load material.

Heat required for moisture content of the inlet material:

If

Heat required for removal of moisture:

If

Heat required for removal of moisture:

Heat required for retained moisture which is assumed to be in liquid (water) form,

Note: The assumption is that retained water is super heated and can be discharged at outlet temperature of the solid. This is an approximation, and in most cases there is very little chance that water can be retained in the solid once its temperature exceeds vaporizing temperature of 212 °F.

Heat required for solid.

If

Heat required to heat the solid material,

If

Heat required to heat the solid material,

Where,

Heat of reaction,

Where

If the reaction is exothermic then,

Total heat required for heating of the material: .

Note that heat required for endothermic reaction is supplied by the heating system (i.e., burners), and the available heat factor should be used to calculate the total heat required from the heating system to accurately calculate the total heat requirement. On the other hand, if the reaction is exothermic, then the available factor should not be applied to this heat since it is subtracted from the total heat requirements.

###### Example

###### Input – Solid Material

This calculation is for solid 1 (of the selected number). Similar calculations are used for other solids (if any).

* Material type: Mild (carbon) steel
* Specific heat – average () = 0.150 Btu/(lb·F)
* Specific heat of water vapor () = 0.481
* Inlet Temperature () = 70 °F
* Outlet temperature () = 2,200 °F
* Melting temperature () = 2,900 °F
* Inlet total mass flow () = 10,000 lb/h
* Moisture content of material at inlet () = 0.1% of total mass flow
* Moisture content of material at outlet () = 0% of total mass flow
* Moisture outlet temperature () = 500 °F
* Heat of reaction () = 100 Btu/lb
* Type of reaction – exothermic
* Percent material reacted () = 1.0%
* Other heat use () = 0 Btu/h

Heat required for moisture content of the inlet material:

Weight of water content in solid material

Weight of dry solid material

Heat required for removal of moisture

()

Heat required for retained which is assumed to be in liquid (water) form

(   
 .00

Heat required for solid

Final temperature is less than the melting temperature of the solid.

Heat required to heat the solid material:

(

Heat of reaction:

() = 9,900 \* (1 – 0.01) \* (0.010) \* 100 = 9,900

This is an exothermic reaction, so the heat required from an external source will not include heat generated by an exothermic reaction. It will be deducted from the gross heat required when the overall heat balance is made. If the reaction was endothermic, then the heat will be added to net heat requirement and applied to the available heat factor for calculating gross heat requirement.

Total net heat to be supplied for heating of the material

= 12,205 + 0.00 + 3,191,551 + 0   
 = 3,204,056 Btu/h

This net heat has to be supplied by the heating system. Actual heat input will be higher and will be calculated in the heat balance section of the PHASTEx tool.

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possible energy savings measures and modifications for the heating system to reduce energy loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” conditions to analyze the effect of the measure and calculate potential energy savings. One or more measures can be applied simultaneously to see the effect of all applicable measures.

Table 3. Modifications – Energy Saving Measures

|  |
| --- |
| Explore possibilities of lowering the final product temperature |
| Preheating the charge or load material entering the furnace |
| Pre-drying to reduce moisture content of the load entering the furnace |
| Maintain charge feed rate as close to the rated capacity as possible. |
| Consider possibility of reducing endothermic reactions by controlling process conditions. |

###### Liquid Material Inputs and Results (for each material)

The following table gives a list of input parameters, units, and symbols used for an example of calculations for liquid materials. PHASTEx allows use of up to three liquid materials, and it is necessary to give input for each of the materials used.

Table 4. Input Parameters – Liquid Material

|  |  |  |
| --- | --- | --- |
| **Input Parameter – Liquid Material** | | |
| **Process Parameters** | **Units** | **Symbol** |
| Specific Heat of Liquid | Btu/(lb-°F) |  |
| Vaporizing Temperature | °F |  |
| Latent Heat of Vaporization | Btu/lb |  |
| Specific Heat of Vapor | Btu/(lb-°F) |  |
| Charge (Liquid)-Feed Rate | lb/h |  |
| Initial Temperature | °F |  |
| Discharge Temperature | °F |  |
| Charge Liquid Vaporized (% of Charge) | % |  |
| Charge Liquid Reacted (% of Charge) | % |  |
| Heat of Reaction | Btu/lb |  |
| Type of Reaction (Endothermic/Exothermic) |  |  |
| Additional Heat Required | % |  |
| Note: Thermal properties (top four items) are given when the material is selected from the database. If not, the user is required to give the required data. | | |

Table 5. Output – Results

|  |  |  |
| --- | --- | --- |
| **Calculation Result** | **Units** | **Symbol** |
| Total Heat for Charge Material - Liquid | Btu/h |  |

###### Constants

This calculator uses thermal and physical properties of the charge material. The properties include specific heat of liquid or gas/vapor phase of the materials, density, vaporizing or other phase change temperature, heat of phase change and heat of reaction if associated with the heating process. Much of this information can be obtained from literature or references listed at the end of this section or from in‑house knowledge and databases developed by the user. The boiling point of moisture is 210°F and specific heat of water vapor is 0.481 Btu/lb·F. These are average values used in calculations.

###### Heat requirement calculation equations

This calculation is for liquid 1 (of the selected number). Similar calculations are used for other liquids if any.

Heat required for the liquid heated to the outlet temperature.

If

Heat required for liquid,

If

Heat required for liquid,

Heat of reaction,

The value of will be positive if the reaction is endothermic and negative if the reaction is exothermic.

Total heat required for heating of the material, .

Note that the heat required for an endothermic reaction is supplied by the heating system (i.e., burners), and the available heat factor should be used to calculate the total heat required from the heating system to accurately calculate total heat requirement. If the reaction is exothermic, then the available factor should not be applied to this heat since it is subtracted from the total heat requirements.

###### Example

###### Input – Liquid Material

This calculation is for liquid 1 (of the selected number). Similar calculations are used for other liquids if any.

* Material type: Liquid A
* Specific heat – average () = 0.48 Btu/(lb·F)
* Vaporizing temperature of the liquid () = 240 °F
* Specific heat of vapor () = 0.25 But/(lb·F)
* Heat of vaporization (latent heat) = 250 Btu/lb
* Inlet Temperature () = 70 °F
* Outlet Temperature () = 320 °F
* Inlet total mass flow () = 1,000 lb/h
* Liquid feed material vaporized () = 100% of total mass flow
* Moisture content of material at outlet () = 0% of total mass flow
* Liquid material reacted () = 25%
* Heat of reaction () = 50 Btu/lb
* Type of reaction (select endothermic or endothermic) – endothermic
* Additional heat required or used () = 0 Btu/h

Heat required for the liquid heated to the outlet temperature

Since

Heat of reaction, = 1,000 \* 0.25 \* 50 = 12,500 Btu/h

The value of is endothermic so it will be added to the total heat required calculated above.

Additional heat required = 0

Total heat required for heating process, = 351,600 + 12,500 = 364,100 Btu/h

Note that heat required for an endothermic reaction is supplied by the heating system (i.e., burners) and the available heat factor should be used to calculate the total heat required from the heating system to accurately calculate the total heat requirement. If the reaction is exothermic, then the available factor should not be applied to this heat sine it is subtracted from the total heat requirements.

###### Output

Total heat required (net heat) for processing liquid 1 = 364,100 Btu/h.

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possibly applicable energy saving measures and modifications for the heating system to reduce energy use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” condition to analyze effect of the measure and calculate potential energy savings. One or more measures can be applied simultaneously to see the effect of all applicable measures.

Table 6. Possible Modifications – Energy Saving Measures

|  |
| --- |
| Explore possibilities of lowering the final product temperature. |
| Preheat the charge or load material entering the furnace. |
| Maintain charge feed rate as close to the rated capacity as possible. |
| Consider possibility of reducing endothermic reactions by controlling process conditions. |

###### Gaseous Material Inputs and Results (for Each Material)

###### Heat requirement calculation equations

PHASTEx allows the user to select three different gaseous or vapor materials as input for the charge/load material. This option allows the solving of heat requirement calculations when the gas/vapor feed material includes several components. For example, calculations can be performed for mixtures of two gases with water vapor to be heated to a certain temperature in a chemical reactor. In this case, it is possible to calculate the total heat requirement by making calculations for different materials that result in one mixed product as output of the process. The following calculation method can be used for **each** component.

Table 7. Input Parameters – Gas

|  |  |  |
| --- | --- | --- |
| **Input Parameter – Gas Material** | | |
| **Process Parameters** | **Units** | **Symbol** |
| Specific Heat of Gas | Btu/(lb- °F) |  |
| Feed Rate for Gas Mixture | lb/h |  |
| Vapor in Gas Mixture (% of Total) | % |  |
| Initial Temperature | °F |  |
| Discharge Temperature | °F. |  |
| Specific Heat of Vapor | Btu/(lb- °F) |  |
| Feed Gas Reacted (% of Total) | % |  |
| Heat of Reaction | Btu/lb |  |
| Type of Reaction (Endothermic/Exothermic) |  |  |
| Additional Heat Required | Btu/h |  |
| Note: Specific heat of gas is given when the material is selected from the database. If not, the user is required to give the required data. | | |

Table 8. Calculation Results

|  |  |  |
| --- | --- | --- |
| **Calculation Result** | **Units** | **Symbol** |
| Total Heat for Charge Material - Gas | Btu/h |  |

###### Constants

This calculator uses thermal and physical properties of the charge material. The properties include specific heat of vapor phase of the materials, heat of the phase change, and heat of reaction if associated with the heating process. Much of this information can be obtained from literature or references listed at the end of this section or from in‑house knowledge and databases developed by the user.

###### Heat requirement calculation equations

This calculation is for gas mixture 1 (of the selected number). Similar calculations are used for other gas mixture if any.

Heat required for the gas mixture heated to the outlet temperature.

Heat required for gas 1,

Heat required for vapor content of the mixture 1, .

Heat of reaction, .

The value of will be positive if the reaction is endothermic and negative if the reaction is exothermic.

Additional heat required as given in the input data.

Total heat required for heating of the material, .

Note that heat required for an endothermic reaction is supplied by the heating system (i.e., burners), and available heat factors should be used to calculate the total heat required from the heating system. If the reaction is exothermic, then the available factor should not be applied to this heat since it is subtracted from the total heat requirements.

###### Example

###### Input – Gas Vapor Mixture

* Material Type: Gas A with vapor
* Specific heat = average ( = 0.24 Btu/(lb·F)
* Feed rate of gas mixture ( = 1,000 lb/h
* Vapor content of the mixture as % of total feed rate () = 15%
* Specific heat of vapor () = 0.5 Btu/lb·F
* Inlet Temperature () = 80OF
* Outlet or discharge Temperature () = 1,150 °F
* Feed gas reacted () = 100 of total mass flow rate
* Heat of reaction () = 80 Btu/lb
* Type of reaction (Select endothermic or endothermic) – endothermic
* Additional heat required or used () = 5,000 Btu/h

Mass flow rate of vapor in gas mixture = 0.15 1,000 = 150 lb/h

Mass flow rate of gas in the mixture = 1,000 – 150 = 850 lb/h

Heat required for gas 1, = 850 0.24 (1,150 – 80) = 218,280

Heat required for vapor content of the mixture 1,

= (0.15) 1,000 0.5 (1,150 – 80) = 80,250 Btu/h

Heat of reaction, = 1,000 1.0 80 = 80,000 Btu/h

The value of will be positive since the reaction is endothermic.

Additional heat required hex = 5,000 Btu/h

Total heat required for heating of the material

= 218,200 + 80250 + 80,000 + 5,000 = 383,530 Btu/h.

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possibly applicable energy saving measures and modifications for the heating system to reduce energy use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” condition to analyze the effect of the measure and calculate potential energy savings. One or more measures can be applied simultaneously to see the effect of all applicable measures.

Table 9. Possible Modifications - Energy Saving Measures

|  |
| --- |
| Explore possibilities of lowering the final product temperature. |
| Preheat the charge or load material entering the furnace. |
| Maintain charge feed rate as close to the rated capacity as possible. |
| Consider possibility of reducing endothermic reactions by controlling process conditions. |

###### References

* *Fundamentals of Engineering Thermodynamics*, by Moran and Shapiro, published by John Wiley

## ATMOSPHERE

###### Description

The term atmosphere represents a special gas or mixture of gases (hydrogen, nitrogen, mixture of H2 and N2 (HN), etc.) introduced in a furnace. The atmosphere gas uses heat from the available heat in a furnace and affects over all energy use or energy intensity of the heating process or cooling process.

###### Inputs

Table 10. Atmosphere Inputs

|  |  |  |
| --- | --- | --- |
| Input | Unit | Symbol |
| Atmosphere Name | Drop Down List |  |
| Atm. Inlet Temperature | °F |  |
| Atm. Outlet Temperature | °F |  |
| Atm. Flow Rate | Scfh |  |
| Correction Factor | None |  |
| Specific Heat | Btu/ (scf - °F) |  |
| \*scfh – Standard cubic feet per hour, measured at 60 °F and atmospheric pressure at sea level. | | |

###### Constants

Reference Temperatures = = 60 °F

Specific heat of the atmosphere. The calculator includes volumetric specific heat value (Btu/[scf. – °F]) at an average temperature in the range of 600 °F to 1,000 °F for most commonly used atmospheres for heat treating and other applications. If it is necessary, the user is advised to use “Other” as an option and insert the appropriate value of volumetric specific heat using another name for the atmosphere.

###### Equations/Calculations

Heat required for atmosphere: under the stated operating conditions:

Note:

1. The correction factor is used to accommodate possible variations in specific heat due to the composition difference for the atmosphere or presence of moisture or other components normally not used. This allows a range of flexibility.
2. If the volume flow rate units are in cubic feet per minute (cfm), then they should be converted to scfm by using following equation.

Where = pressure in lb/(in.2) gauge

###### Example

###### Input

* Atmosphere flow rate = 1,200 standard ft3/h
* Atmosphere inlet temperature = 100 °F
* Atmosphere outlet temperature = 1,400 °F
* Type of atmosphere = Nitrogen
* Average specific heat = 0.02 Btu/scf – °F: This is the average value over the temperature range of atmosphere heating
* Correction factor = 1.0
* Atmosphere pressure is near ambient or 14.7 psig

###### Calculations

Heat required for atmosphere: under operating conditions

1,200 0.02 (1,400 – 100) 1

31,200 Btu/h

For modified conditions, the user may select to reduce volume flow rate from 1,200 scf to 800 scf. The following calculation is used to calculate energy use under the modified operating condition.

Heat required for atmosphere: Hatm\_modified under modified operating conditions:

800 0.02 (1,400 - 250) 1 Btu/h

18,400 Btu/h

Percent fuel savings is calculated as the difference between energy use at the current and modified conditions as the percent of the current usage.

Actual reduction in energy use depends on the available heat, discussed later in this manual, for the system.

###### Assumptions

* The atmosphere composition does not change.
* There is no heat of reaction (endothermic or exothermic) between the atmosphere and materials inside the furnace.

###### Warnings

* If the atmosphere reacts with the material being processed then its composition changes and it is necessary to use appropriate correction factors based on new and old composition properties.

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possibly applicable energy saving measures and modifications for the heating system to reduce energy use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” condition to analyze the effect of the measure and calculate potential energy savings. One or more measures can be applied simultaneously to see the effect of all applicable measures.

* Mod 1 – Increase the inlet temperature of the furnace atmosphere.
* Mod 2 – Reduce outlet temperature of the furnace atmosphere.
* Mod 3 – Reduce the flow rate of the furnace atmosphere and/or limit the excessive ventilation in furnace areas.

###### References

* *Industrial Furnaces*, by Trinks and Mawhinney, Volume II, published by John Wiley

###### Versions

* Initial version, 7/15/2016 by Arvind Thekdi

## AIR OR WATER COOLING LOSSES

###### Description

Water or air cooling protects rolls, bearings, and doors in hot furnace environments, but at the cost of lost energy. These components and their cooling media (water, air, etc.) become the conduit for additional heat losses from the furnace.

###### Inputs

Table 11. Air or Water Cooling Losses Inputs



Table 12. Air or Water Cooling Losses Outputs

|  |  |  |  |
| --- | --- | --- | --- |
| **Input** | **Symbol** | **Unit System** | **Unit** |
| Current Atmosphere Loss |  | Imperial |  |
| Modified Atmosphere Loss |  | Imperial |  |
| Reduction in energy (heat) loss |  | Imperial |  |

###### Equations/Calculations

Heat loss due to air cooling: [[1]](#footnote-1)

Heat loss due to other gas cooling: [[2]](#footnote-2)

Heat loss due to water cooling: Hcooling

Heat loss due to other liquid cooling:

Reduction in energy loss is:

* Reduction in energy loss per hour = , Btu/h
* Annual reduction in energy loss = , MMBtu/h

Note: The correction factor is used to accommodate possible variations in specific heat of air, errors in volumetric flow and temperature measurements. This will allow users to modify the cooling losses as per the real situation in the plant.

###### Example: Air Cooling

###### Input

* Cooling media = Air
* Current air volumetric flow rate , = 2,500 scfm
* Inlet temperature of air , Tin = 80 °F
* Outlet temperature of air, Tout = 280 °F
* Specific heat of air at average air temperature (average value) = 0.02 Btu/(scf·ºF)
* Correction factor = = 1.0

###### Calculations

* = 2,500 60 0.02 (280−80) = 600,000 Btu/h

###### Assumptions

* The specific heat remains for the range of temperature from inlet to outlet.

###### Example: Gas Cooling

###### Input

* Cooling media = Nitrogen
* Cooling gas volumetric flow rate = = 600 scfm
* Inlet temperature of cooling gas = Tin = 80 °F
* Outlet temperature of cooling gas = Tout = 350 °F
* Specific heat of air at average air temperature (average value) = 0.02 Btu/(scf·ºF)
* Correcton factor = = 1.0

###### Calculations

* = 600 60 0.02 (350−80) = 194,400 Btu/h

###### Example: Water Cooling

###### Input

* Cooling media = Water
* Cooling water flow rate , = 100 gpm
* Inlet temperature of cooling water , Tin = 80 °F
* Outlet temperature of cooling water , Tout = 120 °F
* Specific heat of cooling water at average temperature (average value) = 1.00 Btu/(lb·ºF)
* Correction factor = = 1.0

Standard data: Water density in terms of lb/gal = 8.30 lb/gal at 90 °F

###### Calculations

* = 100 60 8.29 1.00 (120–80) = 1,989,600 Btu/h

Density of water is taken as 8.29 lb/gal at an average temperature of 100 °F. Although water density depends upon temperature, it is almost constant at normal ambient temperature. For example, at 60 °F fresh water has a density of 8.338 lb/gal. At 100 °F fresh water has a density of 8.288 lb/gal.

###### Example: Other Liquid Cooling

###### Input

* Cooling media – Ethylene Glycon
* Cooling liquid flow rate = = 100 gpm
* Density of liquid = liquid 9.35 lb/gal
* Inlet temperature of cooling water = Tin = 80 °F
* Out temperature of cooling water = Tout = 210 °F
* Specific heat of cooling liquid at average temperature (average value) = 0.52 Btu/(lb·ºF)
* Correction factor == 1.0

###### Calculations

* = 100 60 9.35 0.52 (210–80) = 3,792,360 Btu/h

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possibly applicable energy saving measures and modifications for the heating system to reduce energy use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” conditions to analyze the effect of the measure and calculate potential energy savings. One or more measures can be applied simultaneously to see the effect of all applicable measures.

* Mod 1 – Reduce or optimize cooling media flow rate, use an improved higher grade material for components, and/or redesign the components to replace water cooling by air cooling.
* Mod 2 – Redesign the components to replace water cooling by air cooling.
* Mod 3 – Improve the insulation material, design, and maintenance for cooled components to increase the inlet temperature.
* Mod 4 – Improve the insulation materials, design, and maintenance for cooled components to decrease the outlet temperature.

###### References

* *North American Combustion Handbook*, Third Edition, Volume 1
* *North American Combustion Handbook*, Volume II
* For water, all properties are calculated from the IAPWS (International Association for the Properties of Water and Steam) IF97 libraries developed for the steam tool. Density and specific heat are not needed.

###### Versions

* Initial version, 2/15/2013 by S.U. Nimbalkar
* Revised version, 8/4/2013 by S.U. Nimbalkar

## FIXTURES, TRAYS, CONVEYOR, ETC. - HEAT LOSSES

###### Description

Many furnaces use equipment to convey the work into and out of the heating chamber, and this can also lead to heat losses. Conveyor belts/product hangers that enter the heating chamber at ambient or lower temperatures and leave at higher temperatures drain energy from the combustion gases. Example: In car bottom furnaces, the hot car structure gives off heat to the room each time it rolls out of the furnace to load or remove work. This lost energy must be replaced when the car is returned to the furnace.

###### Inputs:

Table 13. Fixtures, Trays, Conveyors: Heat Losses Inputs

|  |  |  |  |
| --- | --- | --- | --- |
| **Input** | **Symbol** | **Unit System** | **Unit** |
| Fixture/Tray/ Conveyor Material Name | Drop Down Menu of Materials. If the material name is not in the list – user selects “Other”. | | |
| Specific heat of the material |  | Imperial |  |
| Fixture/ Tray/ Conveyor Weight Feed Rate |  | Imperial |  |
| Fixture/ Tray/ Conveyor Initial Temperature |  | Imperial |  |
| Fixture/ Tray/ Conveyor Final Temperature |  | Imperial |  |
| Correction Factor |  | NA | NA |

###### Equations for Calculations

Heat required to heat the fixture,

Note: The correction factor is used to accommodate possible variations in specific heat of the fixture material, and measurement errors in the mass flow rate and temperature data. This will allow users to modify the fixture heat losses as per the real situation in the plant.

###### Example: Fixture Losses

Input data for fixtures – 1

* Material Type: = Mild (Carbon) steel
* Specific heat – average (Cps) = 0.122 Btu/(lb·ºF)
* Inlet temperature () = 300 °F
* Outlet temperature () = 1,800 °F
* Fixture mass flow () = 1,250 lb/h
* Correction factor () = 1.0

Heat used (loss) for fixtures – 1

Heat required to heat the fixture () = 1,250 0.122 (1,800 – 300) 1.0 = 228,750 Btu/h

###### Assumptions

This calculator assumes that there is no melting or phase change of the fixture material involved.

###### Possible Modifications – Energy Saving Measures

The following list includes commonly and possibly applicable energy saving measures and modifications for the heating system to reduce energy use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” conditions to analyze the effect of the measure and calculate potential energy savings. One or more measures can be applied simultaneously to see the effect of all applicable measures.

* Mod 1 : Change the fixture/conveyance or material
* Mod 2 : Reduce the feed rate by either:
* Reducing the weight of the material of the fixture/conveyor
* Changing the material of the fixture/conveyor
* Alternating material handling methods (belt vs. roller, trays vs. belt)
* Maximizing the loading
* Using a proper load arrangement
* Avoid cooling fixtures when reused and/or return belts and conveyors within the furnace rather than outside to avoid heat loss.

###### References

* Thermal Properties of Various Materials – North American Combustion Handbook, Volume II, Appendix A‑16 and 17.]

## OTHER LOSSES – HOT GAS LEAKAGE

###### Description

Many ovens or furnaces operate at positive pressures. Leakage or exfiltration gases leaving the furnace via openings other than the flue cause heat loss called “hot flue gases leakage heat loss.” This calculator should only be used if the furnace is operating at a positive pressure.

###### Inputs

Table 14. Other Losses - Hot Gas Leakage Inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Input | Symbol | Unit System | Unit |
| Furnace draft (+ positive pressure) | ΔP | Imperial | Inch W.C. |
| Opening area | A | Imperial | ft2 |
| Temperature of gases leaking from the furnace |  | Imperial | °F |
| Ambient temperature |  | Imperial | °F |
| Coefficient of discharge or flow coefficient |  | Imperial | No Unit |
| Specific Gravity of Flue gasses\*\* | SG |  | No Unit (Air = 1) |
| Correction Factor |  | N/A | N/A |
| \*Coefficient of discharge = is based on data provided in the attached graph. depends upon the angle of convergence in degrees (Source: *Eclipse Combustion Engineering Guide*, 1986, Chapter 1, Page # 6).  \*\*Specific density/gravity of flue gases (Air = 1.) = SG [Since specific gravity is the ratio between the density (mass per unit volume) of the actual flue gas and the density of air, specific gravity has no dimension]. | | | |

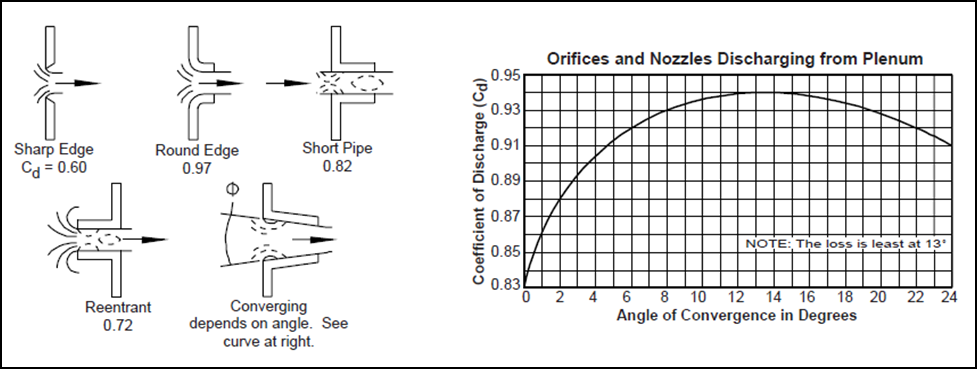


Figure 4. Coefficient of discharge for various types of openings.

###### References

* *Eclipse Combustion Engineering Guide*, E3M, Inc., and North American Handbook, Volume II

Note: The correction factor is used to accommodate possible variations in specific heat of hot flue gases, specific gravity of hot flue gases, or total opening area. This will allow users to modify the hot flue gas leakage losses as per their situation.

###### Equations/Calculations

###### Calculating Air exfiltration from the opening at standard condition (CFH)

Air exfiltration from the furnace opening:

By simplifying the above equation:

As shown in the above equation, the air exfiltration equation requires furnace draft in .

The user provides furnace draft in SI units, Pascals.To convert furnace draft from Pascals to use the following equation.

1 in. w.c. = 0.2488kPa (or) 1 kPa = 4.0193 in. w.c.

Air exfiltration equation requires furnace opening area in . Use the following equation.

Furnace opening area

Air exfiltration from the opening at standard condition,

CFH (Note that, A is ft2 and ΔP is an inch. w.c.)

Density corrected flow in,

Calculating density correct flow (SFH)

Density corrected flow,

###### References

* *Eclipse Combustion Engineering Guide,* 1986, Chapter 1, page 6
* E3M, Inc. and North American Handbook, Volume II

###### Constants

1 Pascal = 1 N/m2 = 1.02 10−4 mH2O

1 in = 39.37 m

1 ft2 = m2 × 10.764

1 MMBtu = 1,000,000 Btu, 1 kJ = 1,000 J, 1 MJ = 1,000,000 J.

###### Example Input and Calculations

Table 15. Example Inputs

|  |  |  |  |
| --- | --- | --- | --- |
| **Input** | **Symbol** | **Unit** | **Value** |
| Furnace draft (+ positive pressure) | ΔP | Inch W.C. | 0.1 |
| Opening area | A | ft2 | 3.0 |
| Temperature of gases leaking from the furnace |  | °F. | 1,600 |
| Ambient temperature |  | °F. | 80 |
| Coefficient of discharge or flow coefficient |  | No Unit | 0.8 |
| Specific Gravity of Flue gasses\*\* | SG | No Unit (Air = 1) | 1.02 |
| Correction Factor |  | N/A | 1.0 |
| \*Coefficient of discharge = is based on data provided in the attached graph. depends upon the angle of convergence in degrees (Source: *Eclipse Combustion Engineering Guide*, 1986, Chapter 1, page 6).  \*\*Specific density/gravity of flue gases (Air = 1.) = SG [Since specific gravity is the ratio between the density (mass per unit volume) of the actual flue gas and the density of air, specific gravity has no dimension]. | | | |

Specific gravity at the gas temperature or =

Gas infiltration Vfg

Note: The PHASTEx calculator uses a value of = 0.8052 for furnace and oven openings. If the user wants to use another value, then it can be accommodated by making appropriate value of correction factor.

Flow rate of the gases in standard conditions,

Specific heat of gases (standard volume basis) at average temperature,

Note: The PHASTEx calculator uses a value of Cd = 0.8052 for furnace and oven openings. If the user wants to use another value, then it can be accommodated by making the appropriate value of correction factor.

Heat content of exfiltrated gases

###### Assumptions

Specific gravity of air is equal to 1. Specific gravity of exhaust gases is measured with respect to air.

###### Warnings

Coefficient of discharge (Cd) for various types of openings can be obtained from different references. Cd depends upon the angle of convergence in degrees. Values of Cd are slightly different in different references.

###### References

* *Eclipse Combustion Engineering Guide*, 1986, Chapter 1, page 6
* *North American Combustion Handbook*, Page 187, Third Edition, Volume 1
* *North American Combustion Handbook*, Volume II, page 62, Figure 7.18

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possibly applicable energy saving measures and modifications for the heating system energy use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” condition to analyze the effect of the measure and calculate potential energy savings. One or more measures can be applied simultaneously to see the effect of all applicable measures.

* Mod 1 – Improve forced air and induction fan controls to maintain slightly positive furnace draft
* Mod 2 – Reduce the size and/or number of openings
* Mod 3 – Maintain optimum furnace temperature

## WALL LOSSES

###### Description

Wall losses are the losses that occur due to heat transferred from the outer surface of the walls or casing of process heating equipment to the surrounding. These losses are in the form of convection heat transfer and radiation heat transfer from the outer wall surfaces. Wall losses are high for systems that are poorly insulated and/or use poorly designed materials.

###### Inputs

Table 16. Wall Losses – Inputs



N/A: Not Applicable

###### Constants

Table 17. Wall Losses – Constants

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Symbol | Definition | Unit system | Constant1 | Unit | Source |
| σ | Stephen-Boltzman’s Constant | SI | 5.6703 × 10−8 |  | 1) ASTM C-680-8  2) Capehart, B., Turner, W., Kennedy, W., *Guide to Energy Management*, 5th Edition, The Fairmont Press, 2005. |
| US | 0.1713 × 10−8 |  |

###### Outputs

###### Equations/Calculations

1. Determine convective loss from the surface area of the walls.

Where,

C = Shape and heat flow condition factor, no units (From Table 2.3.2.1)

d = Diameter of pipe, inches

For flat surfaces and large cylinder of d>24, use d = 24

ETs = existing surface temperature, °F

Ta = ambient air temperature, °F

WV = wind velocity, m/s

SA = surface area, m2

HLCONV = convective heat lost, W

Table 18. Shape Factors for Convection

|  |  |
| --- | --- |
| **Shape and Condition** | **Value of C** |
| Horizontal cylinders | 1.016 |
| Longer vertical cylinders | 1.235 |
| Vertical Plates | 1.394 |
| Horizontal plates, warmer than air, facing upward | 1.79 |
| Horizontal plates, warmer than air, facing downward | 0.89 |
| Horizontal plates, cooler than air, facing upward | 0.89 |
| Horizontal plates, cooler than air, facing downward | 1.79 |
| Source: ASTM C-680-89,Table 1. | |

1. Determine radiation loss from the surface area of the walls.

=

Where,

= emissivity of the surface, 0.9, no units (Table 2.3.2.2 in Appendix)[[3]](#footnote-3)

= Stephen-Boltzman’s constant, 0.1713 × 10−8 

ETs = existing surface temperature, °F

Ta = ambient air temperature, °F

SA = surface area, ft2

HLRAD = Radiation heat loss, Btu/h

1. Sum up the convective and radiation losses from the surface area of the walls to get the value of wall losses and convert for appropriate units.

The unit of wall losses thus calculated is Btu/h.

1. Calculate proposed wall losses ( by following above steps 1 through 3 by substituting proposed surface temperature (PTs) instead of existing surface temperature (ETs). The energy savings are calculated as:
2. The energy savings (reduction in input) are calculated as:

###### Examples and Calculations

###### Input

Table 19. Examples – Inputs

|  |  |  |  |
| --- | --- | --- | --- |
| **Input** | **Symbol** | **Unit** | **Values** |
| Surface area | SA | ft2 | 500 |
| Ambient air temperature | Ta | °F | 80 |
| Existing Surface temperature | ETs | °F | 225 |
| Wind Velocity | WV | Miles per hour | 10.00 |
| Emissivity of the wall outside surface | Ɛw | No Units | 0.90 |
| Shape and Heat Flow Condition Factor | C | No Units | 1.394 |
| Correction factor | Fcorr | No Units | 1.00 |

###### Calculations

These calculations are for a vertical surface representing a vertical wall of a furnace. For this type of vertical surface use d = 24 as given in equation section above.

HLCONV =

HLCONV =

HLCONV = 300,453Btu/h

HLRAD =

HLRAD =

HLRAD = 109,961 Btu/h

= 410,414 Btu/h

###### Assumptions

* Surface emissivity is uniform for the entire surface area.
* Wind velocity is uniform over the entire surface area.

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possibly applicable energy saving measures and modifications for the heating system to reduce energy use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” conditions to analyze effect of the measure and calculate potential energy savings. One or more measure can be applied simultaneously to see the effect of all applicable measures.

Improve the current insulation by either:

* Increasing the insulation thickness.
* Changing the insulation material.
* Changing the furnace wall material using a combination of materials of different insulating properties.
* Insulating the bare surfaces.

###### Warnings

* The furnaces with surface materials having low emittance such as stainless steel or aluminum will have very different heat loss from the vertical surface calcultations above.

###### References

* ASTM C-680 – 89, *Standard Practice for Determination of Heat Gain or Heat Loss and Surface Temperature of Insulated Pipe and Equipment Systems by the Use of a Computer Program*, April 1995.
* Capehart, B., Turner, W., Kennedy, W., *Guide to Energy Management*, 5th Edition, The Fairmont Press, 2005.

###### Versions

Initial version, 03/01/2013 by Arvind Thekdi.

## OPENING LOSSES

###### Description

The losses that occur due to heat transfer through radiation and convection from the openings on process heating equipment walls to the surrounding are called *opening losses*. The losses can be divided into two parts: (i) thermal radiation loss due to exposure of hot furnace interior to the ambient; (ii) and convection or heat loss that results from air infiltration into the furnace due to negative pressure in the furnace or flue gas exfiltration (leakage) from openings due to positive pressure in the furnace. This section deals with heat loss due to thermal radiation from furnace to the ambient background. The “convection” loss is accounted for in two different ways. Air infiltration effect is reflected in increased excess air or O2 content in flue gases and higher flue gas heat loss. When the furnace pressure is positive (with respect to the surrounding area) hot flue gases leak out of the furnace resulting in heat loss in the form of heat in exfiltrated flue gases. These losses are accounted for and calculated in a separate section as other losses. This section only deals with thermal radiation losses.

###### Inputs

Table 20. Opening Losses – Inputs

|  |  |  |  |
| --- | --- | --- | --- |
| **Input** | **Symbol** | **Unit System** | **Unit** |
| Opening Shape | C |  | No Units |
| Diameter or length | D | Imperial | inch |
| Width or height | W | Imperial | inch |
| Furnace wall thickness |  | Imperial | inch |
| Ratio\* | X |  |  |
| Ambient air temperature |  | Imperial | °F |
| Inside Temperature |  | Imperial | °F |
| %Time Open | OF | Imperial | % |
| View Factor\*\* | VF | Imperial | No Units |
| Emissivity | ε | Imperial | No Units |
| \* For a round opening, this is ratio of the opening diameter/furnace wall thickness.  \* For rectangular and square openings, this is the ratio of the smaller dimension [length or height (or width)] of the opening/furnace wall thickness.  \*\* From calculations and graph as described in the following section. | | | |

###### Constants

Table 21. Opening Losses – Constants

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Symbol** | **Definition** | **Unit system** | **Constant1** | **Unit** | **Source** |
| σ | Stephen-Boltzman’s Constant | SI | 5.6703 × 10−8 |  | (1) ASTM C-680-8;  (2) Capehart, B., Turner, W., Kennedy, W., *Guide to Energy Management*, 5th Edition, The Fairmont Press, 2005. |
| US | 0.1713 × 10−8 |  |

###### Equations

1. Determine the shape of the opening by input from user:
   * Circular – Determine diameter.
   * Rectangular – Determine height and width.

Find out ratio using following equation:

1. Determine view factor for the opening using attached graph available as link. The view factor or shape factor value is between 0 to 1.0. For very large openings such as large furnace doors the value is close to 1.0 as shown in Figure 5.

Figure 5. View factor for determination of effective opening losses (Source: PHAST 30).

1. Determine opening losses from the opening area of the walls.

HLRAD =

Where,

= emissivity, no units

= Stephen-Boltzman’s constant, 0.1713 × 10−8

= inside temperature, °F

= ambient air temperature, °F

A = opening area, ft2

= radiation heat loss, Btu/h

OF = percent open time (time open/cycle time)

1. Calculate the opening loss by multiplying the radiation loss, % time open, and view factor.

The unit of opening losses thus calculated is Btu/h.

1. Calculate the proposed opening losses () by using change A, VF, OF, of values. The reduction in opening losses is then obtained as:
2. The energy savings (reduction in input) are calculated as:

###### Example and Calculations

Input data for the case analyzed.

Table 22. Opening Losses - Example Input

|  |  |  |  |
| --- | --- | --- | --- |
| **Input** | **Units** | **Values** | |
| Opening Shape | No Units | 1 - Circle | 2- Rectangular |
| Diameter or length | inch | 12.0 | 48.0 |
| Width or height |  | N/A | 15.0 |
| Furnace wall thickness | No Units | 9.0 | 9.0 |
| Ratio\* | °F | 1.33 | 1.67 |
| Ambient air temperature | °F | 75 | 75 |
| Inside temperature | °F | 1,600 | 1,600 |
| % Time Open | % | 100 | 20 |

Using the input parameters and graphs shown above the following values are derived for further calculations and/or measurements – assumptions.

Table 23. Opening Losses - Input Parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Input** | **Unit** | **Derived or Calculated Values** | |
| Ratio for View Factor | No Units | 1.40 | 0.67 |
| View Factor\*\* | No Units | 0.70 | 0.64 |
| Emissivity | No Units | 095 | 0.95 |

###### Calculations

* **Circle or round opening**
* = 0.70
  + - =
    - = 22,911 Btu/h
    - = 22,911 × 0.7 × (100/100) = 16,038 Btu/h
    - = 16,038 Btu/h
* **Rectangular opening**
* = =0.64
  + - =
    - = 145,861 Btu/h
    - = 145,861 × 0.64 × (20/100) = 18,670 Btu/h
    - = 18,670 Btu/h

###### Assumptions

* The default emissivity is estimated to be 0.95. User can change it if necessary.
* Note: The graphs for view factors are only for four different configurations of the opening. It is suggested that the user use interpolation for other rectangular shapes.

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possibly applicable energy saving measures and modifications for the heating system to reduce use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” conditions to analyze effects of the measure and calculate potential energy savings. One or more measure can be applied simultaneously to see the effect of all applicable measures.

* Mod 1: Minimize the fixed opening size and/or change the fixed openings to variable openings.
* Mod 2: Install tunnel-like extension to minimize radiation losses.
* Mod 3: Close fixed openings, change fixed openings to variable openings, and/or install automatic doors to minimize effective opening time.
* Mod 4: Install curtains such as ceramic strips to minimize fixed opening losses and/or install radiation shields to minimize radiation losses.

###### References

1. Trinks and Mahowney, *Industrial Furnaces*, Volume 1, Fourth Edition, John Wiley and Sons, Inc., New York, 1951.
2. Capehard, B., Turner, W., Kennedy W., *Guide to Energy Management*, 5th Edition, The Fairmont Press, 2005.

###### Versions

* Initial version, 7/302016 by Arvind Thekdi

## FLUE GAS

###### Description

Flue gas losses encompass energy lost through the flue or “chimney” of the furnace. The gasses constitute normally the largest losses in a fired process heating system. The losses are necessary to carry the products of combustion out of the system but can be excessive if more than the minimum amount of air is mixed with fuel. Flue gas losses can be calculated by summing up heat content of components of flue gas. For fossil fuel fired systems, the components include CO2, H2O, N2 and in most cases O2. Depending on the fuel used and combustion conditions, the flue gases may contain small amounts of unburned hydrocarbons, SO2, particles, etc. However, for most industrial systems using cleaner fuels such as natural gas, this small amount of constituents can be ignored. For industrial heating systems, it is difficult and impractical to measure the quantity of each component to calculate the total heat content of the flue gases. Hence, an indirect method known as available heat method is used to calculate heat losses from a heating system. Available heat is expressed as the percentage of the fuel heat input into the system. It is defined as:

Hence

Thus, knowledge of available heat is very useful to calculate the heat content of the flue gases without knowledge of the fuel composition and other detailed information.

PHASTEx uses the following data and associated available heat calculator if necessary for a fuel other than natural gas or hydrocarbon fuel.

###### Input

The flue gas section of PHASTEx uses the following inputs and methodology described later in this section.

Table 24. Flue Gas – Input

|  |  |  |
| --- | --- | --- |
| **Input** | **Unit** | **Symbol** |
| Furnace Flue Gas Temperature | deg. F. |  |
| Select Input (%XS Air or %O2) |  |  |
| Oxygen in Flue Gases (%) | % |  |
| % Excess Air | % |  |
| Combustion Air Temperature | °F |  |
| Available Heat (%) |  |  |

Flue gas temperature is measured at the outlet of the furnace, usually in the stack or chimney at a location as close to the furnace as possible.

Furnace O2 (dry basis) reading is also taken at the same location where flue gas temperature is measured to maintain accuracy of the calculations. In some cases, it may not be possible to collect data for flue gas O2, and it may be necessary to use excess air used for combustion. In this case, it is assumed that there is no additional air leakage into the furnace. For all fuels, there is a definite relationship between O2 content of combustion products (usually assumed to be the same as the flue gas composition). For almost all hydrocarbon fuels, the relationship can be expressed by an empirical equation:

This relationship gives an error of 1% to 2% for most hydrocarbon fuels. However, it is not applicable for “manufactured” fuels such as blast furnace gas, producer gas, or coke oven gas.

The above mentioned equation is used as the default equation for PHASTEx.

Available heat in flue gases depends on the type of fuel, flue gas temperature, mass flow of flue gases and the specific heat of the flue gas. For most fuels, it is possible to calculate available heat as % of fuel input by using detail combustion analysis. A calculator is included as part of PHASTEx to calculate the available heat for a specific fuel when the following parameters are specified:

1. Fuel composition given as volumetric analysis for gaseous fuels and mass analysis for solid and liquid fuels.
2. Flue gas temperature which can be measured by using commonly available temperature measuring instrument.
3. Excess oxygen (O2) on dry basis in flue gas. This can be measured relatively easily.
4. Combustion air temperature.
5. Fuel temperature if substantially different from ambient temperature.

For simplicity, available heat is presented in graphical form for various fuels. An example of available heat for commonly used natural gas is given in the following Figure 6.

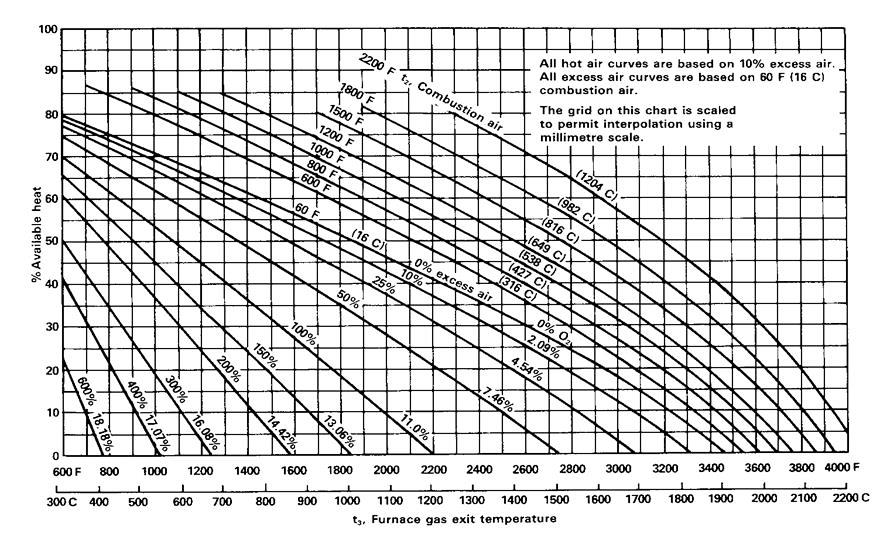


Figure 6. Example of available heat for commonly used natural gas.

Available heat for other fuels can be obtained for a limited range of operating conditions. Figure 7 shows the available heat for gaseous fuels in terms of Btu/ft3 of the fuel used when excess air is zero or O2 content in flue gas is zero.

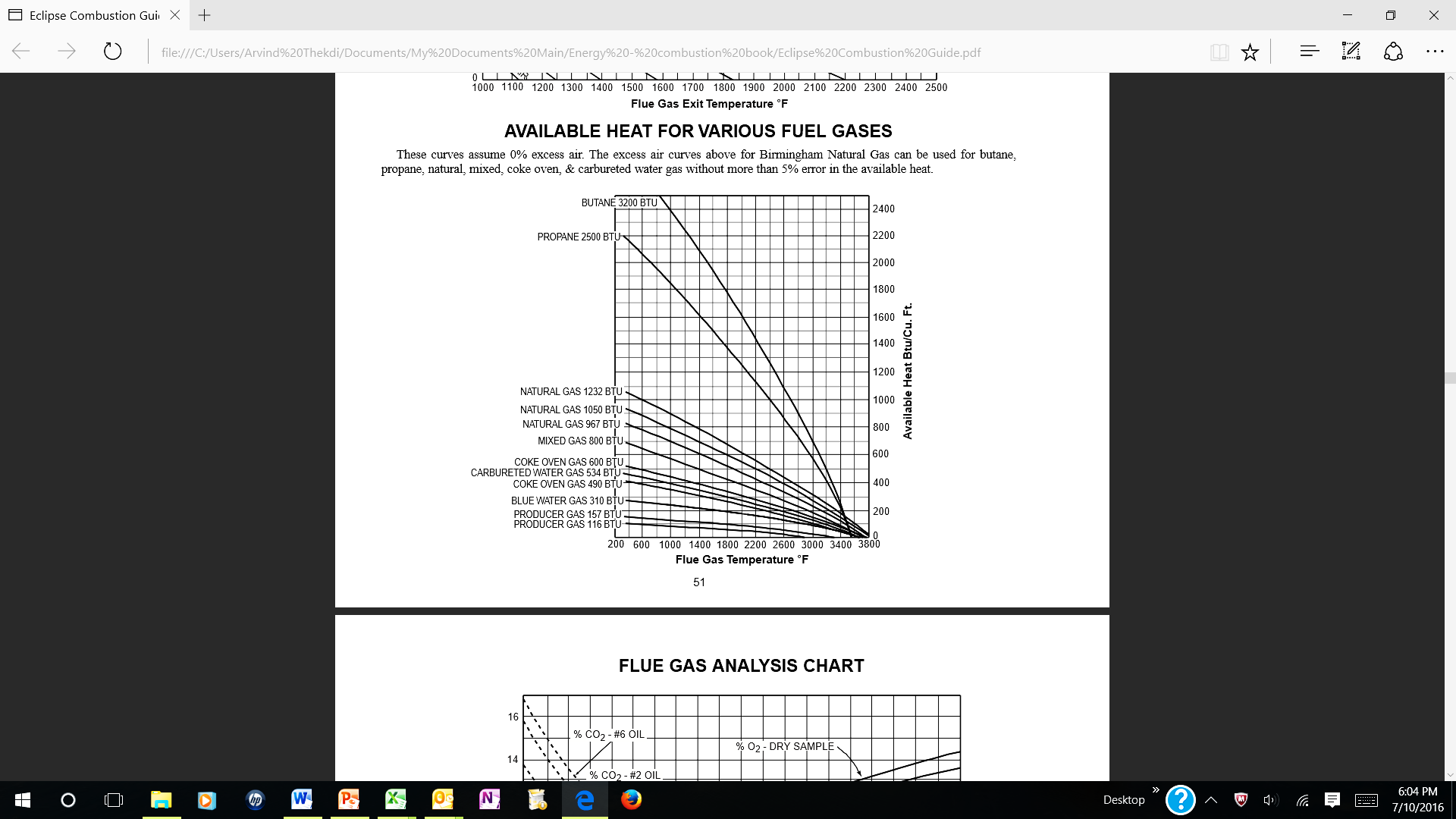


Figure 7. Available heat for various fuel gases.

Available heat calculation methodology is discussed below.

For the calculations, the fuel gas composition is expressed in terms of the components listed in Table 25. This table also shows the chemical composition of the “typical” natural gas used in California. Note that hydrocarbons higher than the C4H10 series are accounted as C4H10. This assumption does not affect the results because the most commonly used natural gas in the United States contains minute amounts of such hydrocarbons, and the error in the results would be very small.

Table 25. Typical fuel (natural gas) components and analysis



The first step is to calculate products of combustion by using standard equations taken from reference 1 and given below.

Figure 3 and 4 are then used to determine the values of specific heat of the flue gas components such as N2, CO2, H2O, etc. These values are used to calculate the total heat content of flue gases.

Where

= Total heat content of the respective flue gas component. Expressed in .

= Mass of the respective flue gas component. Expressed in .

= The specific heat of the respective flue gas component. Expressed in .

= Flue gas temperature expressed in .

= Vaporizing temperature of water at its partial pressure in the flue gases. Expressed in

= The reference temperature. Assumed to be 60 .

= Latent heat of vaporization for water at its partial pressure in flue gases expressed in .

Table 26. Thermal properties for gases



Table 27. Thermal properties for gases, continued



The total heat content of flue gases (Hfg) is the sum of the heat content of all flue gas components (i.e., N2, H2O, CO2).

The amount of available heat is calculated using the following equation:

Where

is the total heat input into the furnace. Expressed inand calculated using

is the total heat in flue gases. Expressed in

is the higher heating value of fuel. Expressed in

is total heat content of combustion air. Expressed in and calculated using

is the specific heat of air. Expressed in

is the total mass of air heated within the unit and includes excess air. Expressed in

This equation gives heat in flue gases if we know the heat input. However, for bottom-up analysis or heat balance, as used in PHASTEx, heat input is unknown. PHASTEx allows calculaing the sum of heat used or lost in various areas of a furnace that represents “net’ heat used in the process.

By definition, available heat is the amount of heat that remains in the furnace, and it represents the sum of all heat used in the furnace. Thus, the sum (Ʃ) of all heat accounted as heat used in the furnace, or “net” ((Hnet)) heat used in the furnace, equals the available heat.

Ʃ (heat used calculated in PHASTEx sheets)

Example with input for use of alternate gaseous fuel.

Input data entered in the flue gas tab using gas O2 as an input parameter.

Table 28. Exhaust Gases Available Heat of Combustion Efficiency



In this case, available heat is calculated using natural gas or similar hydrocarbon fuel as the default fuel. The results show the value of available heat.

Table 29. Value of available heat



Alternatively, the user may enter excess air as an input parameter.

Table 30. Input Parameter Alternative



In this case, available heat is calculated using natural gas or similar hydrocarbon fuel as the default fuel. The results show the value of available heat.

Table 31. Natural gas value of available heat



In this case, where the user would like to select a different fuel, such as coke oven gas, it is necessary to select “Available Heat as User Defined.” It is necessary to select the button “Fuel Analysis by volume percentage” to calculate available heat for the given fuel.



Figure 8. Select Fuel Analysis by weight percentage or by volume percentage.



Figure 9. Available heat calculation for gaseous fuels.

Other input data is the same as above.

Table 32. Exhaust Gases Available Heat or Combustion Efficiency



The results are somewhat different due to high value of H2 and inert gases in fuel gas.

Table 33. Results - High Value of H2



###### Input for use of solid fuel

For solid fuel, the methodology for calculating available heat is very similar, except in this case a different set of equations is used to calculate flue gas composition. This is discussed in the following section.

For the calculations, the fuel gas composition is expressed in terms of the components listed in Table 34. This table also shows the chemical composition of a “typical” natural gas used in California. Note that hydrocarbons higher than the C4H10 series are accounted as C4H10. This assumption does not affect the results since the most commonly used natural gas in the United States contains minute amounts of such hydrocarbons, and error in the results would be very small.

Table 34. Typical fuel (bituminous coal) components and analysis



The first step is to calculate products of combustion by using standard equations taken from reference 1 and given below.

Tables 35 and 36 are then used to determine the values of specific heat of the flue gas components such as N2, CO2, H2O, etc. These values are used to calculate the total heat content of flue gases.

Where

= Total heat content of the respective flue gas component, expressed in

= Mass of the respective flue gas component. Expressed in .

= The specific heat of the respective flue gas component. Expressed in .

= Flue gas temperature expressed in

= Vaporizing temperature of water at its partial pressure in the flue gases. Expressed in .

= The reference temperature. Assumed to be 60

= Latent heat of vaporization for water at its partial pressure in flue gases expressed in

Table 35. Thermal properties for gases



Table 36. Thermal properties for gases continued



The total heat content of flue gases (Hfg) is the sum of the heat content of all flue gas components (i.e. N2, H2O, and CO2).

The amount of available heat is calculated using the following equation.

Where

is the total heat input into the furnace. Expressed inand is calculated using

is the total heat in flue gases. Expressed in.

is the higher heating value of fuel. Expressed in .

is total heat content of combustion air. Expressed in and is calculated using

is the specific heat of air. Expressed in .

is the total mass of air heated within the unit and includes excess air. Expressed in .

This equation gives heat in flue gases if we know the heat input. However, for bottom-up analysis or heat balance as used in PHASTEx, heat input is unknown. PHASTEx allows calculating the sum of heat used or lost in various areas of a furnace that represents “net” heat used in the process.

By definition, available heat is the amount of heat that remains in the furnace, and it represents the sum of all heat used in the furnace. Thus, the sum (Ʃ) of all heat accounted as heat used in the furnace or “net” ((Hnet)) heat used in the furnace equals to the available heat.

Ʃ (heat used calculated in PHASTEx sheets)

###### Example with input for use of alternate gaseous fuel

Input data entered in the flue gas tab using flue gas O2 as the input parameter.

Table 37. Exhaust Gases Available Heat or Combustion Efficiency



In this case, available heat is calculated using natural gas or similar hydrocarbon fuel as default fuel. The results show the value of available heat.

Table 38. Results value of available heat



Alternatively, the user may enter excess air as an input parameter.

Table 39. Excess air as an input parameter



In this case, available heat is calculated using natural gas or similar hydrocarbon fuel as the default fuel. The results show the value of available heat.

Table 40. Results of available heat using natural gas



In cases where the user has selected to use solid fuel (bituminous coal), it is necessary to select “Available Heat as User Defined.” It is necessary to select the button “Fuel Analysis by weight or mass percentage” to calculate available heat for the given fuel.



Figure 10. Select fuel analysis by weight.

The fuel composition or analysis is entered as shown for bituminous coal as an example.

Table 41. Typical fuel (bituminous coal) components and analysis



Other inupt data is the same as above.

Table 42. Exhaust gases available heat or combustion efficiency



The results are somewhat different due to a high value of H2 and inert gases in fuel gas.

Table 43. Available heat



## TYPICAL FUEL COMPOSITION AND HEATING VALUE

###### Gaseous Fuels

Table 44. Typical Gaseous Fuel Composition and Heating Value

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | | **Natural Gas (Louisiana)** | **Propane** | **Blast Furnace Gas** | **Coke Oven Gas** | **Producer Gas** |
| Fuel heat value, (HV) - Volumetric\* | Btu/ft3 | 1,002 | 2,572 | 94 | 560 | 140 |
| kJ/m3 | 37,333 | 95,830 | 3,502 | 20,866 | 5,216 |
| State of the fuel | | Gas | Gas | Gas | Gas | Gas |
| **Composition (%) – Volume Basis** | | | | | | |
| CH4 | | 94.2 |  | - | 28.4 | 2.7 |
| C2H6 | | 2.4 | 2.2 | - | 3.4 |  |
| C3H8 | | 0.49 | 97.3 | - | 0.2 |  |
| C4H10 | | 0.29 | 0.5 |  |  |  |
| H2 | | 0.03 |  | 2.3 | 50.7 | 15 |
| CO | | 0.42 |  | 22.7 | 4.2 | 28.6 |
| CO2 | | 0.71 |  | 19.3 | 0.9 | 3.4 |
| O2 | | 0 |  | 0.7 | 1.6 |  |
| N2 + inert | | 1.46 |  | 55 | 10.6 | 50.3 |
| Total | | 100 | 100 | 100 | 100 | 100 |
| Note: All values are for typical fuels. Each of the stated values may vary significantly depending on the fuel source and other variables. | | | | | | |

Table 45. Typical values for a given fuel

**No. 2 Fuel**

**Oil**

**No. 6 Fuel**

**Oil**

**Bituminou**

**s Coal**

**(Pittsburg**

**h #8)**

**Coke**

**Lignite**

**(Beulah**

**Zap)**

**Tires**

**Wood .**

**Non-**

**resinous**

Btu/US Gal

139,400

153,600

Btu/lb

19,300

18,300

13,859

12,815

10,040

15,500

5950

kJ/kg

44,892

42,566

32,236

29,808

23,353

36,053

13,839

Liquid

Liquid

Solid

Solid

Solid

Solid

Solid

87.3

88.6

80.1

85

44.4

80

37.9

12.5

9.3

5

0.8

2.99

7

7.2

0.2

0.85

1

1

1.35

1.5

0

0.71

5.2

1.2

13.45

3

53.8

0.3

0

1.3

0.76

0.4

0.1

0.04

7.2

10.7

1

0.2

3.1

0.8

26.89

0

Note: These are typical values for a given fuel. In some cases total does not add up to 100

due to factors such as uncertainty in composition, variability in composition etc. It may be

necessary to adjust composition to make total as 100.

O

2

N

2

H

2

O

Fraction of Constituent (X) in fuel unit

Ash

State of the fuel

C

H

2

S

Fuel higher

heat value,

(HHV)\*

Constants used regardless of fuel selected.

Table 46. Fuel Constituents

|  |  |  |
| --- | --- | --- |
| **Fuel Constituent** | **Mol Wt Divisor (Div)** | **O2 Multiplier (Mul)** |
| C to CO2 | 12 | 1 |
| C to CO | 12 | 0.5 |
| CO to CO2 | 28 | 0.5 |
| C unburned, line k | 12 | -- |
| H2 | 2 | 0.5 |
| S | 32 | 1 |
| O2 (deduct) | 32 | −1 |
| N2 | 28 | -- |
| CO2 | 44 | -- |
| H2O | 18 | -- |

###### Outputs

###### Possible Modifications – Energy Saving Measures

The following list includes commonly used and possibly applicable energy saving measures and modifications for the heating system to reduce energy use or loss. Not all measures are applicable under all conditions. The user selects the applicable energy saving measures and corresponding operating parameters under “modified” conditions to analyze the effect of the measure and calculate potential energy savings. One or more measures can be applied simultaneously to see the effect of all applicable measures.

* Mod 1: Control the air-fuel ratio for the burners used in the heating system.
* Mod 2: Minimize air entrainment or entry into the furnace by:
* Controlling furnace/oven pressure or draft to as close to zero value as possible. Values of plus or minus 0.05 in. w.c. are commonly recommended.
* Reduce openings for the furnace/oven.
* Control and minimize use of makeup air, if used, for the oven or dryer.
* Control humidity level or lower explosion limit (LEL) to maintain the required values for safe and efficient operations.
* Use the flue gas heat recovery system to preheat combustion air.
* Minimize the flue gas or exhaust gas temperature by using various means; such as taking exhaust gases out in a lower temperature zone if possible and allowable after considering process performance.
* Use preheated fuel where possible as in cases of use of low heating value fuels such as blast furnace gas or producer gas.

###### References

* *Guide to Industrial Assessments for Pollution Prevention and Energy Efficiency*, EPA/625/R‑99/003
* *Process Heat Tip Sheet #2*, U.S. Department of Energy, DOE/GO-102002-1552

###### Versions

* Initial version, 7/30/2016 by Arvind Thekdi and Sachin Nimbalkar

## POWER USE BY ELECTRIC MOTORS AND OTHER DEVICES

###### Description

Electrical motor systems and other systems using electricity associated with the heating systems and other auxiliary systems consume significant energy. This section can be used to take an inventory of such systems and calculate energy use for such systems.

###### Modifications

1. Use of variable speed drive for motors where possible.
2. Evaluate energy saving measures for pumping systems, fan systems, compressed air systems, etc., to reduce overall motor load resulting from implementation of energy saving measures.

###### Inputs

Table 47. Power Use by Electric Motors and Other Devices

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | | | | |
|  | **Symbol** | **Units** | **Comments** | |
| Name or designation of the drive motor |  | Fans for combustion air; exhaust; or other use | | |
| Electric motor or fan model |  |  | | |
| Pressure (for fans only) | P | psi | | Optional |
| Flow (for fans only) | cfm | ft3/min | | Optional |
| Motor power (name plate) | kW | kW | | Optional |
| Motor phase |  |  | |  |
| Supply voltage | V | Volts | | Measured |
| Average current | A | Amperes | | Measured |
| Power factor (average value) (Default = 0.85) | Pf |  | | Measured |
| % Operating time (as % of total time) (Default = 100%) | %op |  | | Measured |

###### Constants

None

###### Equations/Calculations

For other power using equipment, insert the measured or calculated values. The measurements and calculations depend on the type of power using system and source of information. No specific method is suggested since there are many variations for the system, and it is not possible to cover all of them in this tool or algorithm document.

###### Example

Use of a three-phase electrical motor for driving a combustion air fan or blower.

###### Input

Table 48. Power Use by Electric Motors and Other Devices: Inputs

|  |  |  |
| --- | --- | --- |
|  | | |
| Name or designation of the drive motor | Fans for combustion air; exhaust; or other use | |
| Electric motor or fan model | Fan motor #65 | |
| Pressure (for fans only) | psi | 1 |
| Flow (for fans only) | ft3/h | 1,200 |
| Motor power (name plate) | kW | 8 |
| Motor phase |  | 3 |
| Supply voltage | Volts | 460 |
| Average current | Amperes | 12 |
| Power factor (average value) (Default = 0.85) |  | 0.85 |
| % Operating time (as % of total time) (Default = 100%) |  | 100 |

###### Calculations

* Energy use =

###### Assumptions

* None

###### Versions

* Initial version, 7/30/2016

###### Heat Balance

PHASTEx can be used to prepare a heat balance for furnaces using fossil fuels such as natural gas. The heat balance is based on calculated values of energy use in several areas of a furnace. Energy use for each area under current operating conditions and modified conditions is calculated by using various calculators discussed above. The following steps are used to prepare a heat balance and various reports that allow comparison of the furnace performance under current and modified conditions. Modified conditions heat balance uses operating parameters suggested by the user. These parameters are based on application of various possible energy saving measures suggested for each area of heat use or loss. There may be other measures that are not discussed in this document. The user of the PHASTEx tool makes the final decision on which measures are practical and justifiable. It is possible to perform “What – if” analysis also by analyzing several options. Each case has to be saved separately for comparison of different cases analyzed.

Steps for Heat Balance

1. Calculate the heat required or lost in the applicable areas selected from the following list using PHASTEx calculators.
   1. Load/Charge material: individual solid, liquid, gas component or combination of solid, liquid and gaseous components
   2. Fixture heat requirement
   3. Wall losses
   4. Cooling losses (water, air liquid or gas) for various cooling systems within the furnace
   5. Opening losses (radiation heat loss)
   6. Process atmosphere related losses
   7. Hot gas exfiltration – leakage heat loss
   8. Other heat losses not included above
2. Add all of these losses to calculate net heat required for the furnace
3. Calculate available heat for the furnace using a well-defined system boundary. The system boundary is defined by the areas that are considered in heat use calculations.
4. Calculate flue gas loss using net heat requirement of the furnace and available heat.
5. Calculate total heat input (gross heat) required for the furnace by using values of net heat and available heat or net heat input and flue gas loss.

This process of heat balance is used for current operating conditions and expected operating conditions after selecting application of various energy saving measures.

###### Example

The following is a list of heat losses or heat usage calculated for a furnace. Note that in this case all types of losses are included. However, in most cases only a few losses may exist.

The net heat requirement in the furnace represents heat demand for the furnace, and it has to be supplied by heat input into the furnace. However, when heat is supplied by using fossil fuels, it is always associated with heat loss in flue gas which is generated due to use of fuel and combustion air used in burners or other combustion devices. As mentioned earlier, fuel gas heat losses can be calculated by using available heat for the heating system. In this example, net heat demand for the furnace is 1,087,377 Btu/h.

Table 49. Heat losses calculated for a furnace

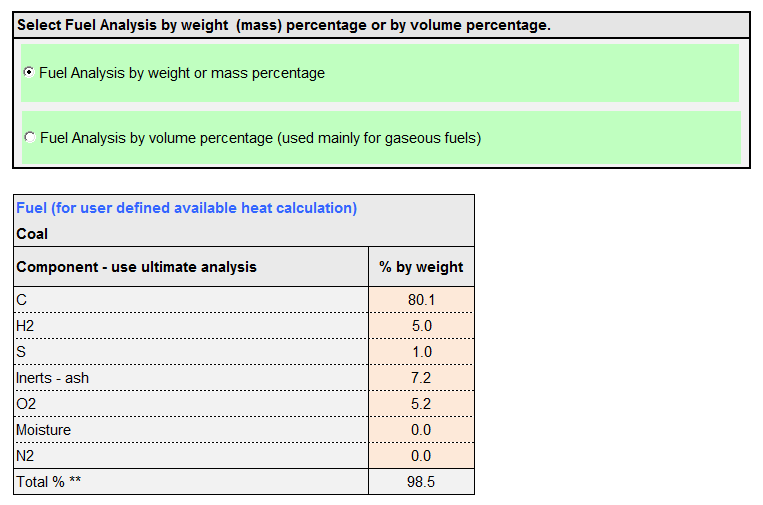
|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Energy Use or Loss Category** | **Energy use - loss (Current)** | |
| **Btu/h** | **MMBtu/h** |
| 1 | Charge material | 666,160 | 0.67 |
| 2 | Fixtures, trays, conveyor etc. | 36,739 | 0.04 |
| 3 | Wall surface heat losses | 150,382 | 0.15 |
| 4 | Water or air cooling (internal) | 66,013 | 0.07 |
| 5 | Atmosphere or makeup air | 22,933 | 0.02 |
| 6 | Radiation losses from openings | 9,875 | 0.01 |
| 7 | Other heat loss or heat addition | 135,275 | 0.14 |
| 8 | **Total net heat required** | **1,087,377** | **1.09** |

Flue gases from the furnace are discharged at 800 °F, and measured O2 (dry basis) is 5%. Combustion air temperature is 70 °F. For the default case that assumes use of natural gas or other similar hydrocarbon fuels, available heat is 71.5%. However, as an example, a case is analyzed where fuel is other than natural gas. In this case, it is assumed that fuel is bituminous coal. The following information is entered in the Flue Gas section to calculate the available heat.

Table 50. Flue Gas section for available heat calculations

|  |  |  |
| --- | --- | --- |
| Furnace Flue Gas Temperature | °F | 800 |
| Select Input (% XS Air or % O2) |  | % Oxygen |
| Oxygen in Flue Gases (%) | % | 5.0 |
| % Excess Air | % |  |
| Combustion Air Temperature | °F | 70 |
| Calculated % O2 in Flue Gas | % | 28.0 |
| Available Heat (%) | % | 71.5 |
| Available Heat (If User Defined) (%) | % | 75.5 |
| Available Heat to Use In Calculation |  | User Defined |
| **Available Heat** | **%** | **75.5** |

Table 51. Fuel Analysis by Weight



Note that the total of all fuel constituents is not 100. The program normalizes the composition to bring the total to 100 before calculating available heat. The calculations show that for this fuel and under the given operating conditions, available heat is 75.5. This value is used to calculate flue gas heat and overall heat input required for the process.

Table 52. Calculations for flue gas heat

|  |  |  |
| --- | --- | --- |
| Excess air for combustion | % | 28 |
| Combustion air temperature | °F | 70 |
| Flue gas temperature | °F | 800 |
| Fuel temperature | °F | 70 |
| Moisture in air combustion (lb H2O/lb of dry air \*) | % | 1.0 |
| Ash discharge temperature | °F | 150 |
| Unburned carbon in ash | % of ash collected | 0.0 |
| \* See psychometric chart below. |  |  |
| \*\* If the total is not exactly 100%, then the program will normalize the component values to get 100% total. |  |  |
|  |  |
| **Available Heat (User Defined) (%)\*** |  | **75.5** |
| \* Based on higher heating value |  |  |

Heat input required

Table 53. Net heat required

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 8 | **Total net heat required** | 1,087,377 | 1.09 |  |
| 9 | Available heat (%) | 75.5 | 75.5% |  |
| 10 | Flue gas loss | 352,903 | 0.35 | 24.50% |
|  | Exothermic heat from process | 0 | 0.00 | 0.00% |
|  | **Total gross heat input required** | **1,440,280** | **1.44** | **100.00%** |

###### References

* *North American Combustion Handbook*, Volume 1, 3rd Edition, North American Mfg. Co., 1986.

###### Results of PHASTEx Analysis

A number of reports are generated to show various areas of energy use or losses and the amount of energy used for each of these areas. Information contained in a report for the current energy use is used to identify areas of energy losses or inefficient use of energy and to make decisions on action items or suggested energy saving measures. The second section of the report shows similar information after entering “modified” operating conditions, which are expected to exist after possible implantation of certain practical energy saving measures. A third report shows comparison of performance in the form of a bar chart and Sankey diagram. The results show heat balance for the system in several units such as Btu/h, kCal/h, MMBtu/h. The heat balance is for current operating conditions and expected operating conditions after implementation of the possible and analyzed energy saving measures.

Figure 11 illustrates an example of a heat balance or distribution of heat developed by using operating data when the heating equipment is operated under current conditions. A similar pie chart is prepared for modified conditions.

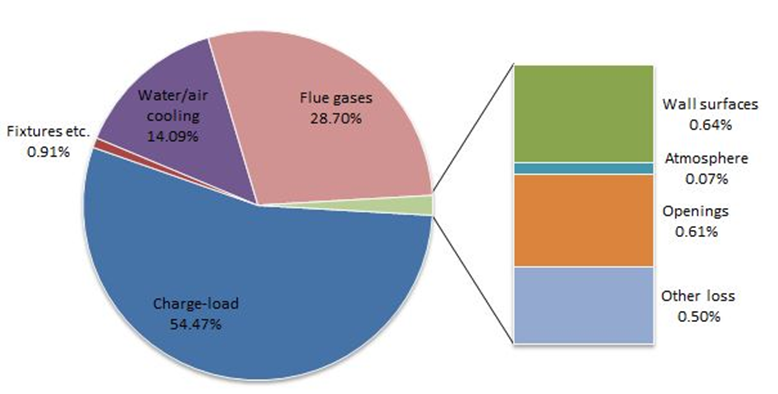


Figure 11. Typical heat distribution results for current operating conditions using PHASTEx.

The report also gives a bar chart for comparison of energy use in various areas under current and modified operating conditions. Figure 12 shows such a chart.

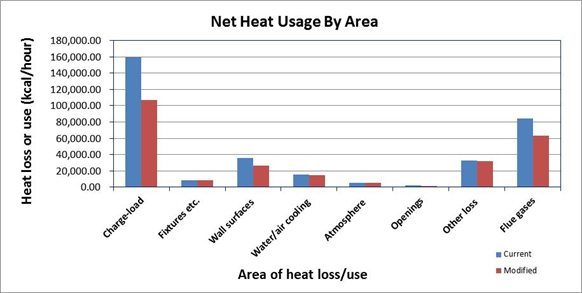


Figure 12. Comparison of energy use with current and modified conditions.

The results are also displayed, as shown in Figure 13, in the form of a “static” Sankey diagram to visualize various losses and use of energy.

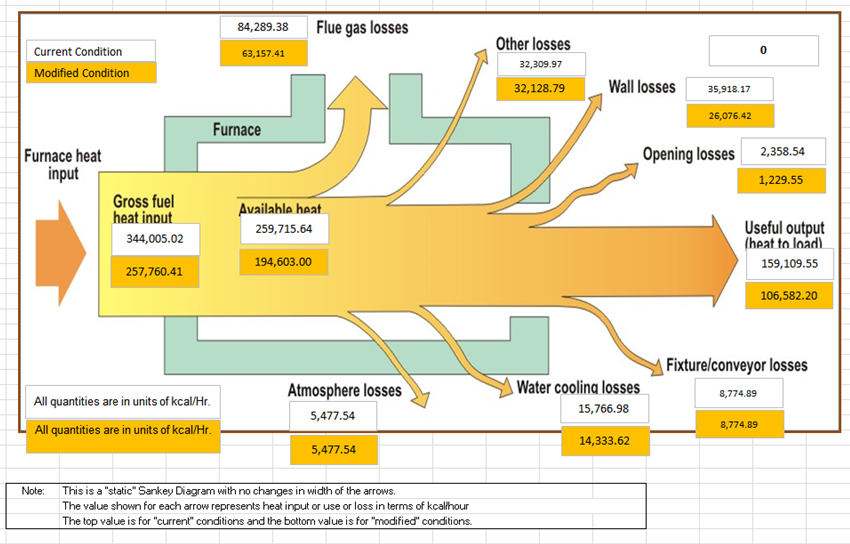


Figure 13. Static Sankey diagram with energy use distribution or heat balance for the furnace under current and modified conditions.

Information given in these reports can be used for comparison of performance of similar equipment at the same location or other plant locations and to take appropriate actions to minimize heat losses resulting in improved performance and energy savings.

1. Emissivity Values

Appendix A. Emissivity Values

Table A-1. Emissivity Values for Different Materials (Source: Omega Engineering)

|  |  |  |  |
| --- | --- | --- | --- |
| **Material** |  | **Temp °F (°C)** | **Emissivity** |
| **Metals** |  |  |  |
| Alloys |  |  |  |
|  | 20-Ni, 24-CR, 55-FE, Oxid. | 392 (200) | 0.9 |
|  | 20-Ni, 24-CR, 55-FE, Oxid. | 932 (500) | 0.97 |
|  | 60-Ni, 12-CR, 28-FE, Oxid. | 518 (270) | 0.89 |
|  | 60-Ni, 12-CR, 28-FE, Oxid. | 1040 (560) | 0.82 |
|  | 80-Ni, 20-CR, Oxidised | 212 (100) | 0.87 |
|  | 80-Ni, 20-CR, Oxidised | 1112 (600) | 0.87 |
|  | 80-Ni, 20-CR, Oxidised | 2372 (1300) | 0.89 |
| Aluminium |  |  |  |
|  | Unoxidised | 77 (25) | 0.02 |
|  | Unoxidised | 212 (100) | 0.03 |
|  | Unoxidised | 932 (500) | 0.06 |
|  | Oxidised | 390 (199) | 0.11 |
|  | Oxidised | 1110 (599) | 0.19 |
|  | Oxidised at 599°C (1110°F) | 390 (199) | 0.11 |
|  | Oxidised at 599°C (1110°F) | 1110 (599) | 0.19 |
|  | Heavily Oxidised | 200 (93) | 0.2 |
|  | Heavily Oxidised | 940 (504) | 0.31 |
|  | Highly Polished | 212 (100) | 0.09 |
|  | Roughly Polished | 212 (100) | 0.18 |
|  | Commercial Sheet | 212 (100) | 0.09 |
|  | Highly Polished Plate | 440 (227) | 0.04 |
|  | Highly Polished Plate | 1070 (577) | 0.06 |
|  | Bright Rolled Plate | 338 (170) | 0.04 |
|  | Bright Rolled Plate | 932 (500) | 0.05 |
|  | Alloy A3003, Oxidised | 600 (316) | 0.4 |
|  | Alloy A3003, Oxidised | 900 (482) | 0.4 |
|  | Alloy 1100-0 | 200-800 (93-427) | 0.05 |
|  | Alloy 24ST | 75 (24) | 0.09 |
|  | Alloy 24ST, Polished | 75 (24) | 0.09 |
|  | Alloy 75ST | 75 (24) | 0.11 |
|  | Alloy 75ST, Polished | 75 (24) | 0.08 |
| Bismuth, Bright |  | 176 (80) | 0.34 |
| Bismuth, Unoxidised |  | 77 (25) | 0.05 |
| Bismuth, Unoxidised |  | 212 (100) | 0.06 |
| Brass |  |  |  |
|  | 73% Cu, 27% Zn, Polished | 476 (247) | 0.03 |
|  | 73% Cu, 27% Zn, Polished | 674 (357) | 0.03 |

| Table A-1. Emissivity Values for Different Materials (Source: Omega Engineering) (continued) | | | |
| --- | --- | --- | --- |
| **Material** |  | **Temp °F (°C)** | **Emissivity** |
|  | 62% Cu, 37% Zn, Polished | 494 (257) | 0.03 |
|  | 62% Cu, 37% Zn, Polished | 710 (377) | 0.04 |
|  | 83% Cu, 17% Zn, Polished | 530 (277) | 0.03 |
|  | Matte | 68 (20) | 0.07 |
|  | Burnished to Brown Colour | 68 (20) | 0.4 |
|  | Cu-Zn, Brass Oxidised | 392 (200) | 0.61 |
|  | Cu-Zn, Brass Oxidised | 752 (400) | 0.6 |
|  | Cu-Zn, Brass Oxidised | 1112 (600) | 0.61 |
|  | Unoxidised | 77 (25) | 0.04 |
|  | Unoxidised | 212 (100) | 0.04 |
| Cadmium |  | 77 (25) | 0.02 |
| Carbon |  |  |  |
|  | Lampblack | 77 (25) | 0.95 |
|  | Unoxidised | 77 (25) | 0.81 |
|  | Unoxidised | 212 (100) | 0.81 |
|  | Unoxidised | 932 (500) | 0.79 |
|  | Candle Soot | 250 (121) | 0.95 |
|  | Filament | 500 (260) | 0.95 |
|  | Graphitized | 212 (100) | 0.76 |
|  | Graphitized | 572 (300) | 0.75 |
|  | Graphitized | 932 (500) | 0.71 |
| Chromium |  | 100 (38) | 0.08 |
| Chromium |  | 1000 (538) | 0.26 |
| Chromium, Polished |  | 302 (150) | 0.06 |
| Cobalt, Unoxidised |  | 932 (500) | 0.13 |
| Cobalt, Unoxidised |  | 1832 (1000) | 0.23 |
| Columbium, Unoxidised |  | 1500 (816) | 0.19 |
| Columbium, Unoxidised |  | 2000 (1093) | 0.24 |
| Copper |  |  |  |
|  | Cuprous Oxide | 100 (38) | 0.87 |
|  | Cuprous Oxide | 500 (260) | 0.83 |
|  | Cuprous Oxide | 1000 (538) | 0.77 |
|  | Black, Oxidised | 100 (38) | 0.78 |
|  | Etched | 100 (38) | 0.09 |
|  | Matte | 100 (38) | 0.22 |
|  | Roughly Polished | 100 (38) | 0.07 |
|  | Polished | 100 (38) | 0.03 |
|  | Highly Polished | 100 (38) | 0.02 |
|  | Rolled | 100 (38) | 0.64 |
|  | Rough | 100 (38) | 0.74 |
|  | Molten | 1000 (538) | 0.15 |
|  | Molten | 1970 (1077) | 0.16 |
|  | Molten | 2230 (1221) | 0.13 |
|  | Nickel Plated | 100-500 (38-260) | 0.37 |
| Dow Metal |  | 0-600 (-18-316) | 0.15 |
| Gold |  |  |  |
|  | Enamel | 212 (100) | 0.37 |
|  | Plate (.0001) |  |  |
|  | Plate on .0005 Silver | 200-750 (93-399) | .11-.14 |
|  | Plate on .0005 Nickel | 200-750 (93-399) | .07-.09 |
|  | Polished | 100-500 (38-260) | 0.02 |
|  | Polished | 1000-2000 (538-1093) | 0.03 |
| Haynes Alloy C, |  |  |  |
|  | Oxidised | 600-2000 (316-1093) | .90-.96 |
| Haynes Alloy 25, |  |  |  |
|  | Oxidised | 600-2000 (316-1093) | .86-.89 |
| Haynes Alloy X, |  |  |  |
|  | Oxidised | 600-2000 (316-1093) | .85-.88 |
| Inconel Sheet |  | 1000 (538) | 0.28 |
| Inconel Sheet |  | 1200 (649) | 0.42 |
| Inconel Sheet |  | 1400 (760) | 0.58 |
| Inconel X, Polished |  | 75 (24) | 0.19 |
| Inconel B, Polished |  | 75 (24) | 0.21 |
| Iron |  |  |  |
|  | Oxidised | 212 (100) | 0.74 |
|  | Oxidised | 930 (499) | 0.84 |
|  | Oxidised | 2190 (1199) | 0.89 |
|  | Unoxidised | 212 (100) | 0.05 |
|  | Red Rust | 77 (25) | 0.7 |
|  | Rusted | 77 (25) | 0.65 |
|  | Liquid | 2760-3220 (1516-1771) | .42-.45 |
| Cast Iron |  |  |  |
|  | Oxidised | 390 (199) | 0.64 |
|  | Oxidised | 1110 (599) | 0.78 |
|  | Unoxidised | 212 (100) | 0.21 |
|  | Strong Oxidation | 40 (104) | 0.95 |
|  | Strong Oxidation | 482 (250) | 0.95 |
|  | Liquid | 2795 (1535) | 0.29 |
| Wrought Iron |  |  |  |
|  | Dull | 77 (25) | 0.94 |
|  | Dull | 660 (349) | 0.94 |
|  | Smooth | 100 (38) | 0.35 |
|  | Polished | 100 (38) | 0.28 |
| Lead |  |  |  |
|  | Polished | 100-500 (38-260) | .06-.08 |
|  | Rough | 100 (38) | 0.43 |
|  | Oxidised | 100 (38) | 0.43 |
|  | Oxidised at 1100°F | 100 (38) | 0.63 |
|  | Gray Oxidised | 100 (38) | 0.28 |
| Magnesium |  | 100-500 (38-260) | .07-.13 |
| Magnesium Oxide |  | 1880-3140 (1027-1727) | .16-.20 |
| Mercury |  | 32 (0) | 0.09 |
|  |  | 77 (25) | 0.1 |
|  |  | 100 (38) | 0.1 |
|  |  | 212 (100) | 0.12 |
| Molybdenum |  | 100 (38) | 0.06 |
|  |  | 500 (260) | 0.08 |
|  |  | 1000 (538) | 0.11 |
|  |  | 2000 (1093) | 0.18 |
|  | Oxidised at 1000°F | 600 (316) | 0.8 |
|  | Oxidised at 1000°F | 700 (371) | 0.84 |
|  | Oxidised at 1000°F | 800 (427) | 0.84 |
|  | Oxidised at 1000°F | 900 (482) | 0.83 |
|  | Oxidised at 1000°F | 1000 (538) | 0.82 |
| Monel, Ni-Cu |  | 392 (200) | 0.41 |
| Monel, Ni-Cu |  | 752 (400) | 0.44 |
| Monel, Ni-Cu |  | 1112 (600) | 0.46 |
| Monel, Ni-Cu Oxidised |  | 68 (20) | 0.43 |
| Monel, Ni-Cu Oxid. at 1110°F |  | 1110 (599) | 0.46 |
| Nickel |  |  |  |
|  | Polished | 100 (38) | 0.05 |
|  | Oxidised | 100-500 (38-260) | .31-.46 |
|  | Unoxidised | 77 (25) | 0.05 |
|  | Unoxidised | 212 (100) | 0.06 |
|  | Unoxidised | 932 (500) | 0.12 |
|  | Unoxidised | 1832 (1000) | 0.19 |
|  | Electrolytic | 100 (38) | 0.04 |
|  | Electrolytic | 500 (260) | 0.06 |
|  | Electrolytic | 1000 (538) | 0.1 |
|  | Electrolytic | 2000 (1093) | 0.16 |
| Nickel Oxide |  | 1000-2000 (538-1093) | .59-.86 |
| Palladium Plate (.00005) |  |  |  |
|  | on .0005 silver | 200-750 (93-399) | .16-.17 |
| Platinum |  | 100 (38) | 0.05 |
|  | " | 500 (260) | 0.05 |
|  | " | 1000 (538) | 0.1 |
| Platinum, Black |  | 100 (38) | 0.93 |
|  |  | 500 (260) | 0.96 |
|  |  | 2000 (1093) | 0.97 |
|  | Oxidised at 1100°F | 500 (260) |  |
|  |  | 1000 (538) | 0.11 |
| Rhodium Flash (0.0002 |  |  |  |
|  | on 0.0005 Ni | 200-700 (93-371) | .10-.18 |
| Silver |  |  |  |
|  | Plate (0.0005 on Ni) | 200-700 (93-371) | .06-.07 |
|  | Polished | 100 (38) | 0.01 |
|  |  | 500 (260) | 0.02 |
|  |  | 1000 (538) | 0.03 |
|  |  | 2000 (1093) | 0.03 |
| Steel |  |  |  |
|  | Cold Rolled | 200 (93) | .75-.85 |
|  | Ground Sheet | 1720-2010 (938-1099) | .55-.61 |
|  | Polished Sheet | 100 (38) | 0.07 |
|  |  | 500 (260) | 0.1 |
|  |  | 1000 (538) | 0.14 |
|  | Mild Steel, Polished | 75 (24) | 0.1 |
|  | Mild Steel, Smooth | 75 (24) | 0.12 |
|  | Mild Steel, | 2910-3270 (1599-1793) |  |
|  | Liquid |  | 0.28 |
|  | Steel, Unoxidised | 212 (100) | 0.08 |
|  | Steel, Oxidised | 77 (25) | 0.8 |
| Steel Alloys |  |  |  |
|  | Type 301, Polished | 75 (24) | 0.27 |
|  | Type 301, Polished | 450 (232) | 0.57 |
|  | Type 301, Polished | 1740 (949) | 0.55 |
|  | Type 303, Oxidised | 600-2000 (316-1093) | .74-.87 |
|  | Type 310, Rolled | 1500-2100 (816-1149) | .56-.81 |
|  | Type 316, Polished | 75 (24) | 0.28 |
|  | Type 316, Polished | 450 (232) | 0.57 |
|  | Type 316, Polished | 1740 (949) | 0.66 |
|  | Type 321 | 200-800 (93-427) | .27-.32 |
|  | Type 321 Polished | 300-1500 (149-815) | .18-.49 |
|  | Type 321 w/BK Oxide | 200-800 (93-427) | .66-.76 |
|  | Type 347, Oxidised | 600-2000 (316-1093) | .87-.91 |
|  | Type 350 | 200-800 (93-427) | .18-.27 |
|  | Type 350 Polished | 300-1800 (149-982) | .11-.35 |
|  | Type 446, Polished | 300-1500 (149-815) | .15-.37 |
|  | Type 17-7 PH | 200-600 (93-316) | .44-.51 |
|  | Type 17-7 PH |  |  |
|  | Polished | 300-1500 (149-815) | .09-.16 |
|  | Type C1020 |  |  |
|  | Oxidised | 600-2000 (316-1093) | .87-.91 |
|  | Type PH-15-7 MO | 300-1200 (149-649) | .07-.19 |
| Stellite, Polished |  | 68 (20) | 0.18 |
| Tantalum, Unoxidised |  | 1340 (727) | 0.14 |
|  |  | 2000 (1093) | 0.19 |
|  |  | 3600 (1982) | 0.26 |
|  |  | 5306 (2930) | 0.3 |
| Tin, Unoxidised |  | 77 (25) | 0.04 |
|  |  | 212 (100) | 0.05 |
| Tinned Iron, Bright |  | 76 (24) | 0.05 |
|  |  | 212 (100) | 0.08 |
| Titanium |  |  |  |
|  | Alloy C110M |  |  |
|  | Polished | 300-1200 (149-649) | .08-.19 |
|  | Oxidised at |  |  |
|  | 538°C (1000°F) | 200-800 (93-427) | .51-.61 |
|  | Alloy Ti-95A |  |  |
|  | Oxid. at |  |  |
|  | 538°C (1000°F) | 200-800 (93-427) | .35-.48 |
|  | Anodized onto SS | 200-600 (93-316) | .96-.82 |
|  |  |  |  |
| Tungsten |  |  |  |
|  | Unoxidised | 77 (25) | 0.02 |
|  | Unoxidised | 212 (100) | 0.03 |
|  | Unoxidised | 932 (500) | 0.07 |
|  | Unoxidised | 1832 (1000) | 0.15 |
|  | Unoxidised | 2732 (1500) | 0.23 |
|  | Unoxidised | 3632 (2000) | 0.28 |
|  | Filament (Aged) | 100 (38) | 0.03 |
|  | Filament (Aged) | 1000 (538) | 0.11 |
|  | Filament (Aged) | 5000 (2760) | 0.35 |
| Uranium Oxide |  | 1880 (1027) | 0.79 |
| Zinc |  |  |  |
|  | Bright, Galvanised | 100 (38) | 0.23 |
|  | Commercial 99.1% | 500 (260) | 0.05 |
|  | Galvanised | 100 (38) | 0.28 |
|  | Oxidised | 500-1000 (260-538) | 0.11 |
|  | Polished | 100 (38) | 0.02 |
|  | Polished | 500 (260) | 0.03 |
|  | Polished | 1000 (538) | 0.04 |
|  | Polished | 2000 (1093) | 0.06 |
|  |  |  |  |
| **Non-Metals** |  |  |  |
| Adobe |  | 68 (20) | 0.9 |
| Asbestos |  |  |  |
|  | Board | 100 (38) | 0.96 |
|  | Cement | 32-392 (0-200) | 0.96 |
|  | Cement, Red | 2500 (1371) | 0.67 |
|  | Cement, White | 2500 (1371) | 0.65 |
|  | Cloth | 199 (93) | 0.9 |
|  | Paper | 100-700 (38-371) | 0.93 |
|  | Slate | 68 (20) | 0.97 |
|  | Asphalt, pavement | 100 (38) | 0.93 |
|  | Asphalt, tar paper | 68 (20) | 0.93 |
| Basalt |  | 68 (20) | 0.72 |
| Brick |  |  |  |
|  | Red, rough | 70 (21) | 0.93 |
|  | Gault Cream | 2500-5000 (1371-2760) | .26-.30 |
|  | Fire Clay | 2500 (1371) | 0.75 |
|  | Light Buff | 1000 (538) | 0.8 |
|  | Lime Clay | 2500 (1371) | 0.43 |
|  | Fire Brick | 1832 (1000) | .75-.80 |
|  | Magnesite, Refractory | 1832 (1000) | 0.38 |
|  | Grey Brick | 2012 (1100) | 0.75 |
|  | Silica, Glazed | 2000 (1093) | 0.88 |
|  | Silica, Unglazed | 2000 (1093) |  |
|  | Sandlime | 2500-5000 (1371-2760) | .59-.63 |
| Carborundum |  | 1850 (1010) | 0.92 |
| Ceramic |  |  |  |
|  | Alumina on Inconel | 800-2000 (427-1093) | .69-.45 |
|  | Earthenware, Glazed | 70 (21) | 0.9 |
|  | Earthenware, Matte | 70 (21) | 0.93 |
|  | Greens No. 5210-2C | 200-750 (93-399) | .89-.82 |
|  | Coating No. C20A | 200-750 (93-399) | .73-.67 |
|  | Porcelain | 72 (22) | 0.92 |
|  | White Al2O3 | 200 (93) | 0.9 |
|  | Zirconia on Inconel | 800-2000 (427-1093) | .62-.45 |
| Clay |  | 68 (20) | 0.39 |
|  | Fired | 158 (70) | 0.91 |
|  | Shale | 68 (20) | 0.69 |
|  | Tiles, Light Red | 2500-5000 (1371-2760) | .32-.34 |
|  | Tiles, Red | 2500-5000 (1371-2760) | .40-.51 |
|  | Tiles, Dark Purple | 2500-5000 (1371-2760) | 0.78 |
| Concrete |  |  |  |
|  | Rough | 32-2000 (0-1093) | 0.94 |
|  | Tiles, Natural | 2500-5000 (1371-2760) | .63-.62 |
|  | Brown | 2500-5000 (1371-2760) | .87-.83 |
|  | Black | 2500-5000 (1371-2760) |  |
| Cotton Cloth |  | 68 (20) | 0.77 |
| Dolomite Lime |  | 68 (20) | 0.41 |
| Emery Corundum |  | 176 (80) | 0.86 |
| Glass |  |  |  |
|  | Convex D | 212 (100) | 0.8 |
|  | Convex D | 600 (316) | 0.8 |
|  | Convex D | 932 (500) | 0.76 |
|  | Nonex | 212 (100) | 0.82 |
|  | Nonex | 600 (316) | 0.82 |
|  | Nonex | 932 (500) | 0.78 |
|  | Smooth | 32-200 (0-93) | .92-.94 |
| Granite |  | 70 (21) | 0.45 |
| Gravel |  | 100 (38) | 0.28 |
| Gypsum |  | 68 (20) | .80-.90 |
| Ice, Smooth |  | 32 (0) | 0.97 |
| Ice, Rough |  | 32 (0) | 0.98 |
| Lacquer |  |  |  |
|  | Black | 200 (93) | 0.96 |
|  | Blue, on Al Foil | 100 (38) |  |
|  | Clear, on Al Foil (2 coats) | 200 (93) | .08 (.09) |
|  | Clear, on Bright Cu | 200 (93) | 0.66 |
|  | Clear, on Tarnished Cu | 200 (93) | 0.64 |
|  | Red, on Al Foil (2 coats) | 100 (38) |  |
|  | White | 200 (93) |  |
|  | White, on Al Foil (2 coats) | 100 (38) | .69 (.88) |
|  | Yellow, on Al Foil (2 coats) | 100 (38) | .57 (.79) |
| Lime Mortar |  | 100-500 (38-260) | .90-.92 |
| Limestone |  | 100 (38) | 0.95 |
| Marble, White |  | 100 (38) | 0.95 |
|  | Smooth, White | 100 (38) | 0.56 |
|  | Polished Grey | 100 (38) | 0.75 |
| Mica |  | 100 (38) | 0.75 |
| Oil on Nickel |  |  |  |
|  | 0.001 Film | 72 (22) | 0.27 |
|  | 0.002 " | 72 (22) | 0.46 |
|  | 0.005 " | 72 (22) | 0.72 |
|  | Thick Film | 72 (22) | 0.82 |
| Oil, Linseed |  |  |  |
|  | On Al Foil, uncoated | 250 (121) | 0.09 |
|  | On Al Foil, 1 coat | 250 (121) | 0.56 |
|  | On Al Foil, 2 coats | 250 (121) | 0.51 |
|  | On Polished Iron, .001 Film | 100 (38) | 0.22 |
|  | On Polished Iron, .002 Film | 100 (38) | 0.45 |
|  | On Polished Iron, .004 Film | 100 (38) | 0.65 |
|  | On Polished Iron, Thick Film | 100 (38) | 0.83 |
| Paints |  |  |  |
|  | Blue, Cu2O3 | 75 (24) | 0.94 |
|  | Black, CuO | 75 (24) | 0.96 |
|  | Green, Cu2O3 | 75 (24) | 0.92 |
|  | Red, Fe2O3 | 75 (24) | 0.91 |
|  | White, Al2O3 | 75 (24) | 0.94 |
|  | White, Y2O3 | 75 (24) | 0.9 |
|  | White, ZnO | 75 (24) | 0.95 |
|  | White, MgCO3 | 75 (24) | 0.91 |
|  | White, ZrO2 | 75 (24) | 0.95 |
|  | White, ThO2 | 75 (24) | 0.9 |
|  | White, MgO | 75 (24) | 0.91 |
|  | White, PbCO3 | 75 (24) | 0.93 |
|  | Yellow, PbO | 75 (24) | 0.9 |
|  | Yellow, PbCrO4 | 75 (24) | 0.93 |
| Paints, Aluminium |  | 100 (38) | .27-.67 |
|  | 10% Al | 100 (38) | 0.52 |
|  | 26% Al | 100 (38) | 0.3 |
|  | Dow XP-310 | 200 (93) | 0.22 |
| Paints, Bronze |  | Low | .34-.80 |
|  | Gum Varnish (2 coats) | 70 (21) | 0.53 |
|  | Gum Varnish (3 coats) | 70 (21) | 0.5 |
|  | Cellulose Binder (2 coats) | 70 (21) | 0.34 |
| Paints, Oil |  |  |  |
|  | All colors | 200 (93) | .92-.96 |
|  | Black | 200 (93) | 0.92 |
|  | Black Gloss | 70 (21) | 0.9 |
|  | Camouflage Green | 125 (52) | 0.85 |
|  | Flat Black | 80 (27) | 0.88 |
|  | Flat White | 80 (27) | 0.91 |
|  | Grey-Green | 70 (21) | 0.95 |
|  | Green | 200 (93) | 0.95 |
|  | Lamp Black | 209 (98) | 0.96 |
|  | Red | 200 (93) | 0.95 |
|  | White | 200 (93) | 0.94 |
| Quartz, Rough, Fused |  | 70 (21) | 0.93 |
|  | Glass, 1.98 mm | 540 (282) | 0.9 |
|  | Glass, 1.98 mm | 1540 (838) | 0.41 |
|  | Glass, 6.88 mm | 540 (282) | 0.93 |
|  | Glass, 6.88 mm | 1540 (838) | 0.47 |
|  | Opaque | 570 (299) | 0.92 |
|  | Opaque | 1540 (838) | 0.68 |
| Red Lead |  | 212 (100) | 0.93 |
| Rubber, Hard |  | 74 (23) | 0.94 |
| Rubber, Soft, Grey |  | 76 (24) | 0.86 |
| Sand |  | 68 (20) | 0.76 |
| Sandstone |  | 100 (38) | 0.67 |
| Sandstone, Red |  | 100 (38) | .60-.83 |
| Sawdust |  | 68 (20) | 0.75 |
| Shale |  | 68 (20) | 0.69 |
| Silica,Glazed |  | 1832 (1000) | 0.85 |
| Silica, Unglazed |  | 2012 (1100) |  |
| Silicon Carbide |  | 300-1200 (149-649) | .83-.96 |
| Silk Cloth |  | 68 (20) | 0.78 |
| Slate |  | 100 (38) | .67-.80 |
| Snow, Fine Particles |  | 20 (-7) | 0.82 |
| Snow, Granular |  | 18 (-8) | 0.89 |
| Soil |  |  |  |
|  | Surface | 100 (38) | 0.38 |
|  | Black Loam | 68 (20) | 0.66 |
|  | Plowed Field | 68 (20) | 0.38 |
| Soot |  |  |  |
|  | Acetylene | 75 (24) | 0.97 |
|  | Camphor | 75 (24) | 0.94 |
|  | Candle | 250 (121) | 0.95 |
|  | Coal | 68 (20) | 0.95 |
| Stonework |  | 100 (38) | 0.93 |
| Water |  | 100 (38) | 0.67 |
| Waterglass |  | 68 (20) | 0.96 |
| Wood |  | Low | .80-.90 |
|  | Beech Planed | 158 (70) | 0.94 |
|  | Oak, Planed | 100 (38) | 0.91 |
|  | Spruce, Sanded | 100 (38) | 0.89 |

1. Actual volume rate should be converted from cfm to scfm since the specific heat is given for standard volume conditions. This is only applicable for air and other gases. [↑](#footnote-ref-1)
2. Actual volume rate should be converted from cfm to scfm since the density is at standard conditions. This is only applicable for air and other gases. [↑](#footnote-ref-2)
3. User can leave a default of 0.9 (high) or look-up a value for appropriate surface from the table provided in the appendix. [↑](#footnote-ref-3)