Evaporation & Wort Boiling

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John Hancock – Briggs of Burton
Evaporation & Wort Boiling - Contents

- Boiling & Evaporation - Basics
- Wort Boiling Process
- Whisky Distillation Process
- Boiling & Condensation Heat Transfer
- Heat Transfer – Fouling, ΔT & Surface Area
- Wort Boiling Systems
- Energy Recovery
- Wort Boiling vs Product Quality
Boiling & Evaporation – Phase Change

• Phase Change
  – Liquid to Vapour – Energy Intensive
  – Specific heat of Evaporation – $h_{fg}$
    • Energy to evaporate 1 kg
    • Water - $h_{fg} = 2257 \text{ kJ/kg at atm pressure}$
  – Boil Energy input
    • e.g. 5% volume off 1000 hl
      $= M_E \times h_{fg}$
      $M_E = \text{Mass Water Evaporated}$
      $= 1000 \text{ hl } \times (5/100) \times 100 \text{ kg/L} = 5000 \text{ kg}$
      $= 5000 \text{ kg } \times 2257 \text{ kJ/kg } = 11,285,000 \text{ kJ}$
      $= 11,285 \text{ MJ}$
Boiling & Evaporation – Energy Intensive

• Energy Intensive
  – **Boil** 5% off 1000 hl
    
    \[
    = 11,285,000 \text{ kJ} = 11,285 \text{ MJ}
    \]
  – **Pre-boil** - Heat 1000 hl wort – 75 to 100 °C
    
    \[
    = M \times C_p \times (T_2 - T_1)
    \]
    
    Mass \( M = 1000 \text{ hl} \times 100 \text{ kg/L} = 100,000 \text{ kg} \)

    Specific Heat \( C_p \) kJ/kg K
    
    Energy to heat 1 kg by 1 °C (or °K)
    
    Water = 4.2 kJ/kg K
    
    Wort = 4.0 kJ/kg K
    
    \[
    = 100,000 \times 4.0 \times (100 - 75) = 10,000,000 \text{ kJ}
    \]
    
    = 10,000 MJ
Boiling & Evaporation – Energy Flow

• Boil 5% off 1000 hl
  – Heat Input = 11,285,000 kJ
  – 60 minute boil
  – Q = 11,285,000 / (60 x 60) = 3,134 kW

• Heat 1000 hl wort – 75 to 100 °C
  – Heat Input = 10,000,000 KJ
  – 50 minutes heating
  – Q = 10,000,000 / (50 x 60) = 3,333 kW
Boiling & Evaporation – Steam Flow

• Steam
  • Most commonly used heating media for large scale efficient heating processes
  • Condensation –
    – Vapour to Liquid
    – Reverse of Boiling
  • Specific Heat of Condensation – $h_{fg}$
    – Same as Heat of Evaporation
    – Energy released on condensing 1 kg
    – Steam (Water) - $h_{fg} = 2133 \text{ kJ/kg at 3 bar g}$
    – Lower than at atm pressure (2257 kJ/kg)
Boiling & Evaporation – Steam Flow

- Energy in = Energy out
- Boil 5% off 1000 hl
  
  \[ Q = 3,134 \text{ kW} \]
  
  Steam Flow = \( \frac{3,134 \text{ kW}}{2133 \text{ kJ/kgK}} \)
  
  = 1.47 kg/s = 5,290 kg/h
  
  Steam Flow similar to Evaporation rate
  
  5,290 kg/h Steam (6% higher) vs 5,000 kg/h Evap

- Heat 1000 hl wort – 75 to 100 °C

  \[ Q = 3,333 \text{ kW} \]
  
  Steam Flow = \( \frac{3,333 \text{ kW}}{2133 \text{ kJ/kgK}} \)
  
  = 1.56 kg/s = 5,625 kg/h

Note – Ignores Heat Losses
Wort Boiling Process

• Wort Boiling Objectives
  – Why Boil?
  – How?
    • Process Requirements
    • Affect on –
      – Downstream processes
      – Product quality

• Batch vs Continuous Boiling
  • Predominantly a Batch process – high peak loads
  • Continuous boiling reduces utility peak loads
Wort Boiling Objectives – Why Boil?

- **Flavour Development**
  - Volatile Removal
  - Isomerisation
- **Wort Clarity** –
  - Trub Formation - Flocculation
- **Stabilisation**
  - Sterilisation
  - Enzyme Inactivation
- **Concentration** - Gravity / Volume
### Achieving Objectives – How?

<table>
<thead>
<tr>
<th>Objective</th>
<th>Process Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile Removal</td>
<td>Evaporation &amp; Turbulence</td>
</tr>
<tr>
<td>Isomerisation</td>
<td>Temperature &amp; Time</td>
</tr>
<tr>
<td>Flocculation</td>
<td>Vigorous Boil (Wort/vapour interface - bubbles), Low Shear</td>
</tr>
<tr>
<td>Sterilisation &amp; Enzyme Inactivation</td>
<td>Temperature &amp; Time</td>
</tr>
<tr>
<td>Gravity / Volume</td>
<td>Evaporation</td>
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Evaporation itself is not the key process in Wort Boiling, Other factors are more critical.
Whisky Distillation Process

• Malt Whisky Distillation – Pot Stills
  – Wash 8% alcohol
  – Spirit 60 % alcohol
  – Water evaporation = large energy input
  – 66% of Distillery energy input

• Two (or 3) stage process
  – Wash Stills – major evaporation / energy load
  – Spirit Stills
  – Batch Distillation – 2 or 3 stage
Whisky Distillation Process

- Evaporation higher as % of feed than wort boiling
  - 30 to 40% of initial volume / stage
- Changes through Batch Distillation –
  - Wash / Spirit temperature increases
  - Alcohol concentration drops
# Heat Transfer Coefficients

## Boiling & Condensation

<table>
<thead>
<tr>
<th>Boiling</th>
<th>Condensation</th>
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</thead>
<tbody>
<tr>
<td><strong>Film Boiling</strong> –</td>
<td><strong>Film Condensation</strong> –</td>
</tr>
<tr>
<td>• Vapour insulates liquid from surface</td>
<td>• Surface Permanently wet</td>
</tr>
<tr>
<td>• Vapour conductivity low</td>
<td>• Thin liquid film flowing down tubes</td>
</tr>
<tr>
<td>• Poor heat transfer</td>
<td>• Vertical tubes – Velocity increases down tube</td>
</tr>
<tr>
<td>• Rapid fouling</td>
<td>• Horizontal tubes – Flow from tube to tube</td>
</tr>
<tr>
<td></td>
<td>• Liquid Conductivity high</td>
</tr>
<tr>
<td></td>
<td>• Good Heat Transfer</td>
</tr>
<tr>
<td><strong>Nucleate Boiling</strong> –</td>
<td><strong>Dropwise Condensation</strong> –</td>
</tr>
<tr>
<td>• Vapour forms in small bubbles</td>
<td>• Surface not wet</td>
</tr>
<tr>
<td>• Bubbles quickly leave surface</td>
<td>• Droplets form</td>
</tr>
<tr>
<td>• Increases turbulence</td>
<td>• Quickly run off leaving surface bare</td>
</tr>
<tr>
<td>• Good heat Transfer</td>
<td>• Very High Heat Transfer Rates</td>
</tr>
</tbody>
</table>
Boiling - Surface & Temperature

- Boiling Mode affected by –
  - Temperature Difference
  - Surface ‘Wettability’

- Copper
  - ‘Wettable’
  - Vapour bubbles easily released
  - Film boiling only at very high ΔT

- Stainless Steel
  - Non-Wettable
  - Vapour clings to surface
  - Film boiling can occur at low ΔT
Boiling – Heat Transfer Modes

**Forced Convection**
- Turbulence through high liquid velocity
- Low $\Delta T$ or high back pressure
- High flowrate and/or multi pass heat exchange

**Nucleate Boiling**
- Turbulence through bubbling & two phase flow
- Moderate $\Delta T$ 'wettable' surface
- Minimal back pressure

**Film Boiling**
- Laminar vapour film blankets surface
- High $\Delta T$ 'non-wettable' surface
- Rapid fouling
Heat Transfer - Nucleate Boiling

Most commonly used mode for boiling wort.
- Internal Heater
- External Thermosyphon

Vapour Bubbles Beneficial
1) Protein Denaturation & Coagulation
2) Volatile Stripping
3) Hop Acid Isomerisation

Intensity of Boil
The more steam vapour bubbles formed per unit volume of wort the more intense the boil

The Difference in Density Between Single Phase & Two Phase is the Driving Force for the Thermosyphon

Single Phase Flow (Liquid)

Two Phase Flow (Liquid & Vapour)
Heat Transfer - Fouling, Area & $\Delta T$

- $Q = U \times A \times \Delta T$
  - $U$ – Heat Transfer Coefficient
    - Higher for Nucleate Boiling
    - Low for Film Boiling
    - Fouling reduces $U$ progressively
  - $A$ – Surface Area
    - Low Surface Area needs higher $\Delta T$
  - $\Delta T$ – Temperature Difference – Driving Force
    - Low $\Delta T$ needs Large Surface Area
    - Low $\Delta T$ reduces fouling
Wort Boiling Heat Transfer – Surface Area

Typical Internal Heater Surface Area
0.08 M²/HL

Typical British External Thermosyphon
0.2 M²/HL

Open Tangential Return Above Wort Surface

Temperature Profile across Clean Heater Surface

Internal Heater Steam 2.2 Bar 137 °C

External Heater Steam 0.6 Bar 115 °C

Wort Boiling Point (100 °C)

The Difference Between Heater Surface Contact Temperature and Wort Boiling Point Determines The Degree Of Evaporation

Higher surface area lowers heater surface temperature in contact with wort. Lower Delta T is considered beneficial for foam, flavour & flavour stability.
The larger external Heater will reach this degree of fouling after 25 brews, then needing 1.5 Bar steam @ 127 °C. The smaller Internal Heater would reach the same degree of fouling after 10 brews. This would require 6.5 Bar Steam @ 168 °C, which is not advisable. Normally wort heaters are limited to 4 Bar steam to avoid film boiling and therefore the small internal heater will require CIP after 5-6 Brews.
Wort Boiling Technology

- Internal Wort Heaters (IWH)
- External Wort Heaters (EWH)
  - Pumped
  - Thermosyphon
- Kettle-Whirlpools
- Control
- Steam Injection
Internal Wort Heater

- Traditional
  - e.g. North America

- Percolators
  - Very low Surface area

- Tubular Internal Heater
  - Low Surface Area
    - Typically 0.08 m²/hl

- Needs frequent CIP

- Fountain & Spreader

- May be pump assisted
  - Similar to External Heater
Internal Wort Heater - Technology

- Tubular Internal Heater: Good Circulation/Mixing
- Coil/Jackets: Poor Circulation/Mixing
- Forced Circulation "Internal" Heater
EWH – Fountain & Spreader

- Flexible
  - Brewlength
  - CIP volume
- Fountain & Spreader
- Thermosyphon
  - low shear
  - Typically 0.2 m²/hl
- Or Forced Circulation
  - Pumped
  - high shear
External Wort Heating Development

Original 1960's Kalandria System
Pump Assisted Circulation

Forced Circulation 3 Pass System With Throttle Valve
Forced Convection High Shear

Thermosyphon Kalandria System
Natural Circulation Nucleate Boiling Low Shear
EWH – Fountain & Spreader
EWH – Symphony

- Thermosyphon
- Tangential Inlet
  - Low Shear
- Boil on the whirl
  - Improved Mixing
- 2 Phase flow
  - Vapour / Liquid interface
  - Volatile Stripping
- EWH – High Surface Area
  - Vapour bubble formation
EWH – Symphony

CUB, Yatala - Australia
Twin stream Brewhouse
10 brews / day, 825 hl cold wort
Symphony Wort Boiling and Energy Recovery systems
Kettle-Whirlpools

Combined Wort Boiling + Trub Separation

- Forced Circulation
  - High Shear

- Thermosyphon
  - ‘Symphony Plus’
EWH – Symphony Plus

• Combined Kettle & Whirlpool
• Thermosyphon Circulation
• Eliminates Transfer to Whirlpool
• Reduced shear
• Improved Trub Separation
Steam Injection

- Steam Condenses directly into Wort
  - No Heater / Fouling
  - Condensate dilutes wort, offsetting heat input

- Steam Quality
  - As steam condenses into wort – Steam must be of process quality
  - Culinary steam
    - Filtered
    - FDA approved additives
    - Stainless Steel steam system (pipework)
Wort Boiling Control

- Energy in = Energy out
- Mass evaporated is proportional to mass of steam condensed
- If uncontrolled, fouling slows heat transfer which reduces steam mass flow and reduces evaporation
- Steam control valve automatically opens to increase steam temperature (pressure) to restore the target rate of steam condensation.
Wort Boiling - Energy Minimisation

• Wort Boiling - Major Energy User
• Minimise Evaporation
  – Wort Quality
• Energy Recovery –
  – MVR
  – TVR
  – Energy Store
    • Wort Pre-heating
Wort Boiling - Energy Minimisation

Wort Boiling - Major Energy User

Historical data for a 10% Boil without Energy Recovery

- Bottling T 20%
- Mashing T 14%
- Kettle Boil T 20%
- Kettle Raise T 12%
- Heating & Other T 14%
- Fridge E 10%
- Pumps E 8%
- Lighting E 2%

Same Data with 4% Boil with Wort Preheating using Energy Recovery

- Bottling T 25%
- Mashing T 18%
- Kettle Boil T 10%
- Kettle Raise T 5%
- Heating & Other T 14%
- Fridge E 13%
- Pumps E 10%
- Lighting E 2%
Wort Boiling – Reduce Evaporation

• 1 % reduction in evaporation
  – saves approximately 2 to 4% of Brewhouse energy consumption
  – (1 to 2% of total brewery energy consumption)
  – and reduces emissions

• Improved kettle utilisation –
  – reduced wort heater CIP frequency

• Easy to implement on existing wort kettles

• Dependent on recipe there is a point at which reduced evaporation will change beer character
MVR – Mechanical Vapour Compression
MVR – Mechanical Vapour Compression

• Direct Recycling of Boil Energy
  – Minimal Thermal Boil Energy Requirement
• Replaced with smaller Electrical Power Input
  – Electricity Requirement 0.1 - 0.7 kWh/hl
• High Capital Investment
  – Long Payback Period (>3 years)
• Large rotating machine – Maintenance
• Difficult to Maintain Air Free Wort Boiling
• Contaminated condensed vapour limits reuse
TVR – Thermal Vapour Compression

- VAPOUR
- KETTLE
- VAPOUR
- VALVE
- VENT
- MOTIVE STEAM 7 - 24 bar a
- STEAM JET VAPOUR COMPRESSOR
- MIXED VAPOURS & STEAM 1.2 – 1.7 bar a (0.2 to 0.7 bar g)
- EWH
- CONDENSATE
TVR – Thermal Vapour Compression

- Lower Capital cost than MVR
- Recycles 50% or less of boil thermal energy
  - Reduced Energy saving
  - Can be combined with Energy Store to increase recovery
    - Dual system – increased complexity & cost
- Requires high pressure steam for recompression
  - typically 10 bar g or higher
- Contaminated condensed vapour limits reuse
Energy Store – Wort Pre-heating

Energy Recovery Tank

Underback

Wort Kettle

Mash Filter

Wort Pre-heater

Energy Recovery System
Energy Store, Condenser & Pre-heater

Energy Store Tank

Condenser

Pre-heater
Energy Store – Wort Pre-heating

• 68% to 80% of Wort Heating Energy saved by using recovered boil energy
• Minimum 3.6% evaporation to recover enough heat for Wort Preheating.
  – Where evaporation exceeds this, excess recovered energy may be used for CIP or water heating
• Moderate cost
• Simple system with few moving parts and no high pressure / temperature
• Pre-run & energy store tank required
• Reduces Wort Boiling fouling & CIP
Energy Store – Wort Pre-heating Energy Reduction

• Heating Energy = $M \times C_p \times (T_2 - T_1)$

• No Energy Recovery
  – Heat 1000 hl wort – 75 to 100 °C
    $= 100,000 \times 4.0 \times (100 - 75) = 10,000,000 \text{ kJ}$
    $= 10,000 \text{ MJ}$

• With Wort Pre-heating to 92 °C
  – Heat 1000 hl wort – 92 to 100 °C
    $= 100,000 \times 4.0 \times (100 - 92) = 3,200,000 \text{ kJ}$
    $= 3,200 \text{ MJ}$

• Energy Saving = 10,000 MJ - 3,200 MJ = 6,800 MJ
  $= 68\%$ reduction
  Steam Saving = 6,800,000 kJ / 2,133 kJ/kg = 3,188 kg/brew
Wort Boiling Systems & Wort Quality

• Wort Boiling System Design Considerations
  – Boiling - Evaporation Heat Transfer
  – Wort Quality
    • Volatile stripping
    • Trub
    • Stability / foam

• Wort Quality
  – Affect of agitation / shear on hot & cold break
  – Wort Quality vs Evaporation & Heater Area
  – Comparative results
Hot Break & Cold Break vs Agitation

- A vigorous well mixed boil enhances trub formation
- Excessive shear breaks up hot break (trub)
  - Creating more cold break
  - Filtration problems downstream
Increase in Anti Radical Potential - DPPH

830 hl 6.5%/h x 70 min boil -
- Existing Internal Heater
- New Symphony EWH System (boil on whirl) 0.22 m²/hl
Reduction in Furfural levels

![Bar chart showing reduction in furfural levels between old and new brewhouses.]

830 hl 6.5%/h x 70 min boil -
- Existing Internal Heater
- New Symphony EWH System (boil on whirl) 0.22 m²/hl
ESR Lag Time

830 hl 6.5%/h x 70 min boil -
- Existing Internal Heater
- New Symphony EWH System (boil on whirl) 0.22 m²/hl
830 hl 6.5%/h x 70 min boil -
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Evaporation & Wort Boiling