Evaporation & Wort Boiling

IBD/BFBi Midlands Section Engineering Symposium on Heat Transfer and Refrigeration

Burton-on-Trent – Jan 2014

John Hancock – Briggs of Burton

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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 kJ/kg at atm pressure
  - Boil Energy input
    - e.g. 5% volume off 1000 hl

$= M_E \times h_{fg}$ $\quad\quad M_E$ = Mass Water Evaporated

– M_E = 1000 hl x (5/100) x 100 kg/L = 5,000 kg

= 5,000 kg x 2257 kJ/kg = 11,285,000 kJ

=11,285 MJ

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Boiling & Evaporation – Energy Intensive

- Energy Intensive
  - Boil 5% off 1000 hl

    =11,285,000 kJ = 11,285 MJ
  - Pre-boil - Heat 1000 hl wort – 75 to 100 °C

    $= M \times C_P \times (T_2 - T_1)$

    Mass M = 1000 hl x 100 kg/L = 100,000 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 x 4.0 x (100 – 75) = 10,000,000 kJ

    = 10,000 MJ

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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

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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 kJ/kg at 3 bar g
    - – Lower than at atm pressure (2257 kJ/kg)

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Boiling & Evaporation – Steam Flow

- Energy in = Energy out
- Boil 5% off 1000 hl

  Q = 3,134 kW

  Steam Flow = 3,134 kW / 2133 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 kW

  Steam Flow = 3,333 kW / 2133 kJ/kgK

  = 1.56 kg/s = 5,625 kg/h

Note – Ignores Heat Losses

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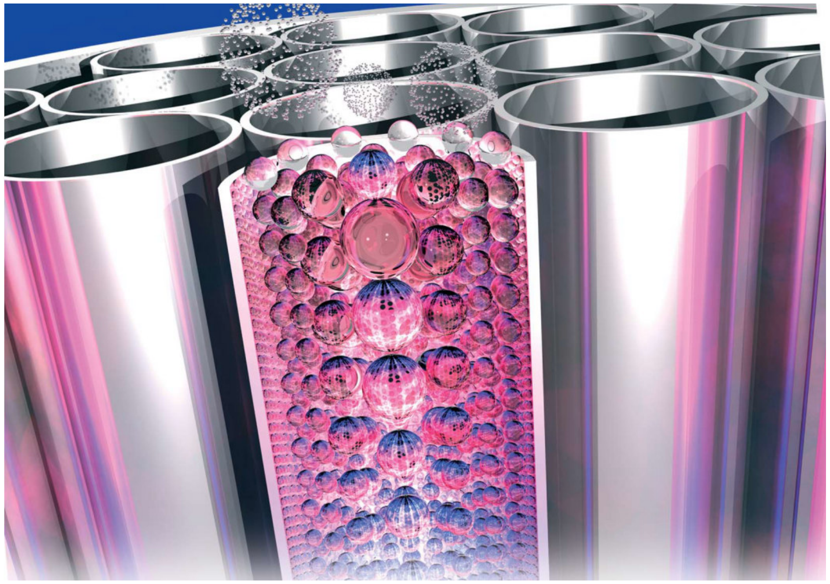
Wort Boiling Process

- 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

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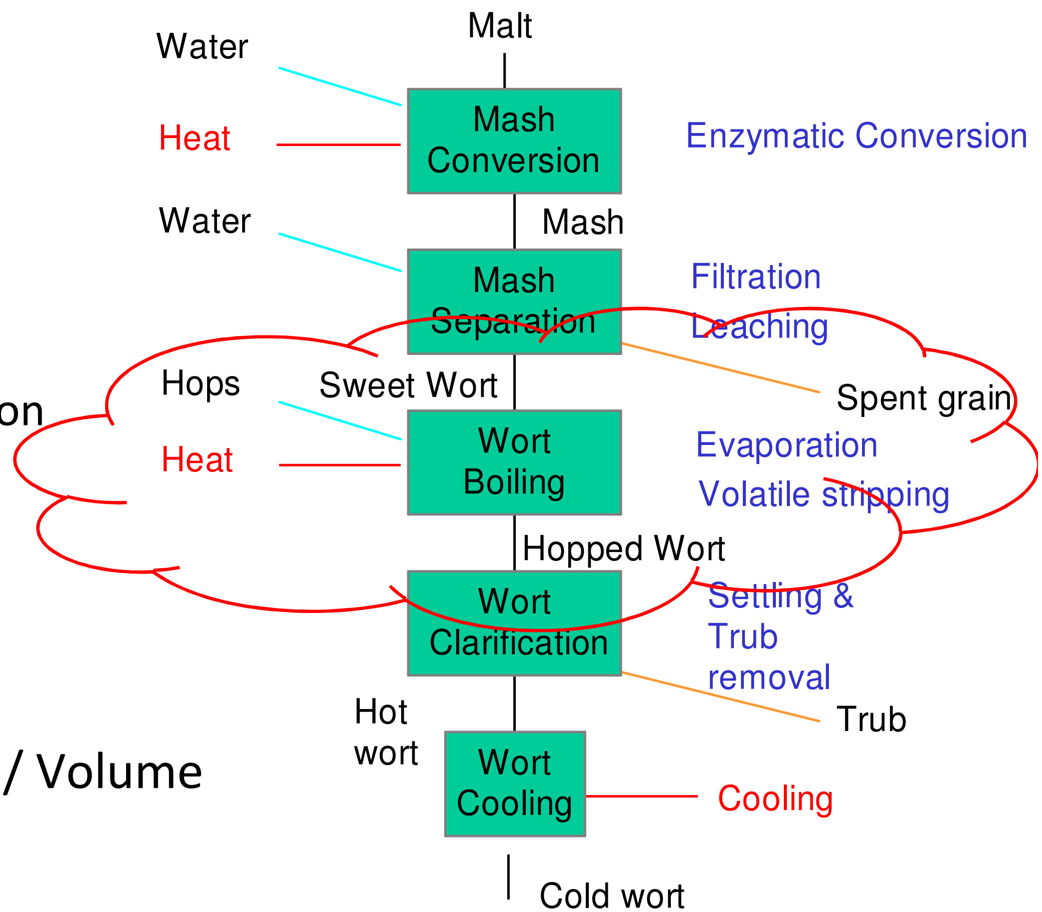
Wort Boiling Objectives – Why Boil?

- Flavour Development
  - Volatile Removal
  - Isomerisation
- Wort Clarity –
  - Trub Formation - Flocculation
- Stabilisation
  - Sterilisation
  - Enzyme Inactivation
- Concentration - Gravity / Volume



Achieving Objectives – How?

Objective	Process Factors
Volatile Removal	Evaporation & Turbulence
Isomerisation	Temperature & Time
Flocculation	Vigorous Boil (Wort/vapour interface - bubbles), Low Shear
Sterilisation & Enzyme Inactivation	Temperature & Time
Gravity / Volume	Evaporation

Evaporation itself is not the key process in Wort Boiling,
Other factors are more critical.

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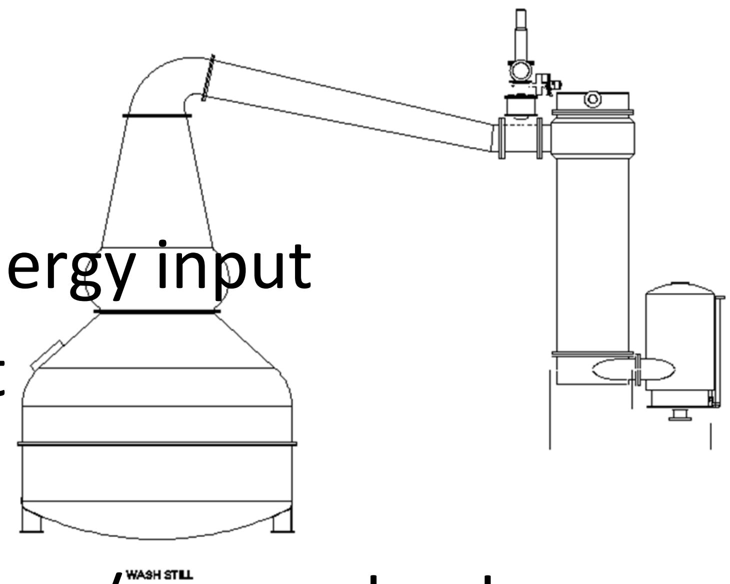
Whisky Distillation Process

- 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

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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

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Heat Transfer Coefficients
Boiling & Condensation

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

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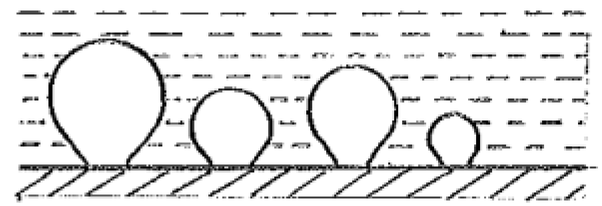
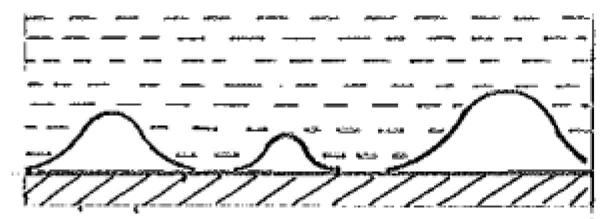
Boiling - Surface & Temperature

- 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



COPPER – 'WETTABLE'

Vapour Bubbles released



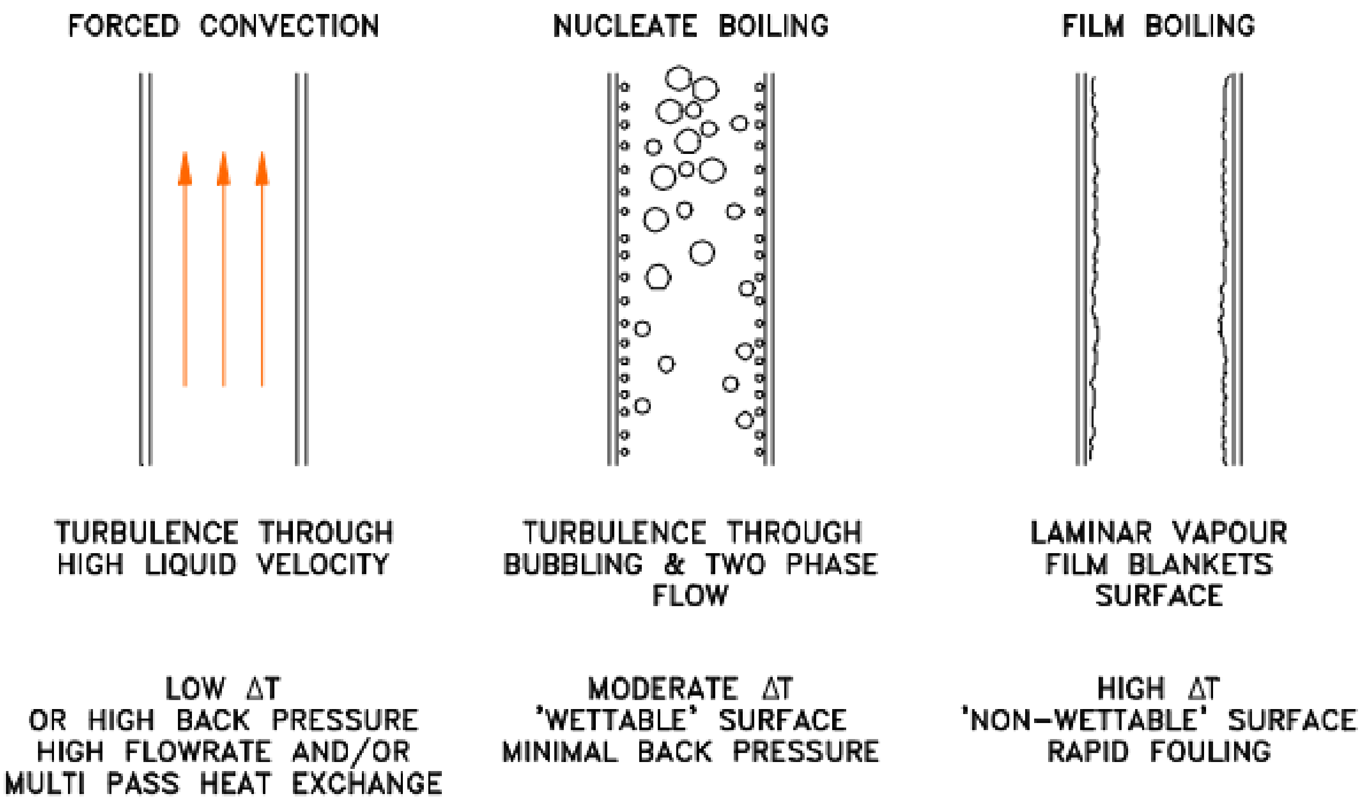
STAINLESS STEEL –

'NON-WETTABLE'

Vapour bubbles cling

to surface.

Boiling – Heat Transfer Modes



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Heat Transfer - Nucleate Boiling

Most commonly used mode for boiling wort.

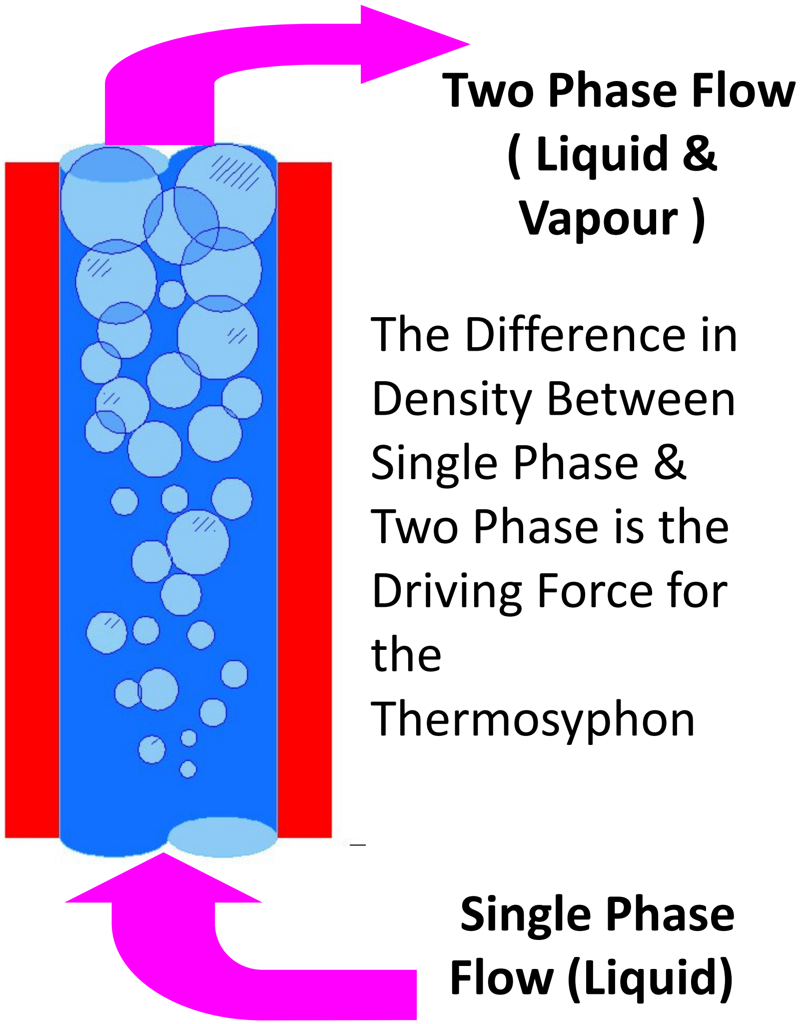
- **Internal Heater**
- **External Thermosyphon**

<u>Vapour Bubbles Beneficial</u>

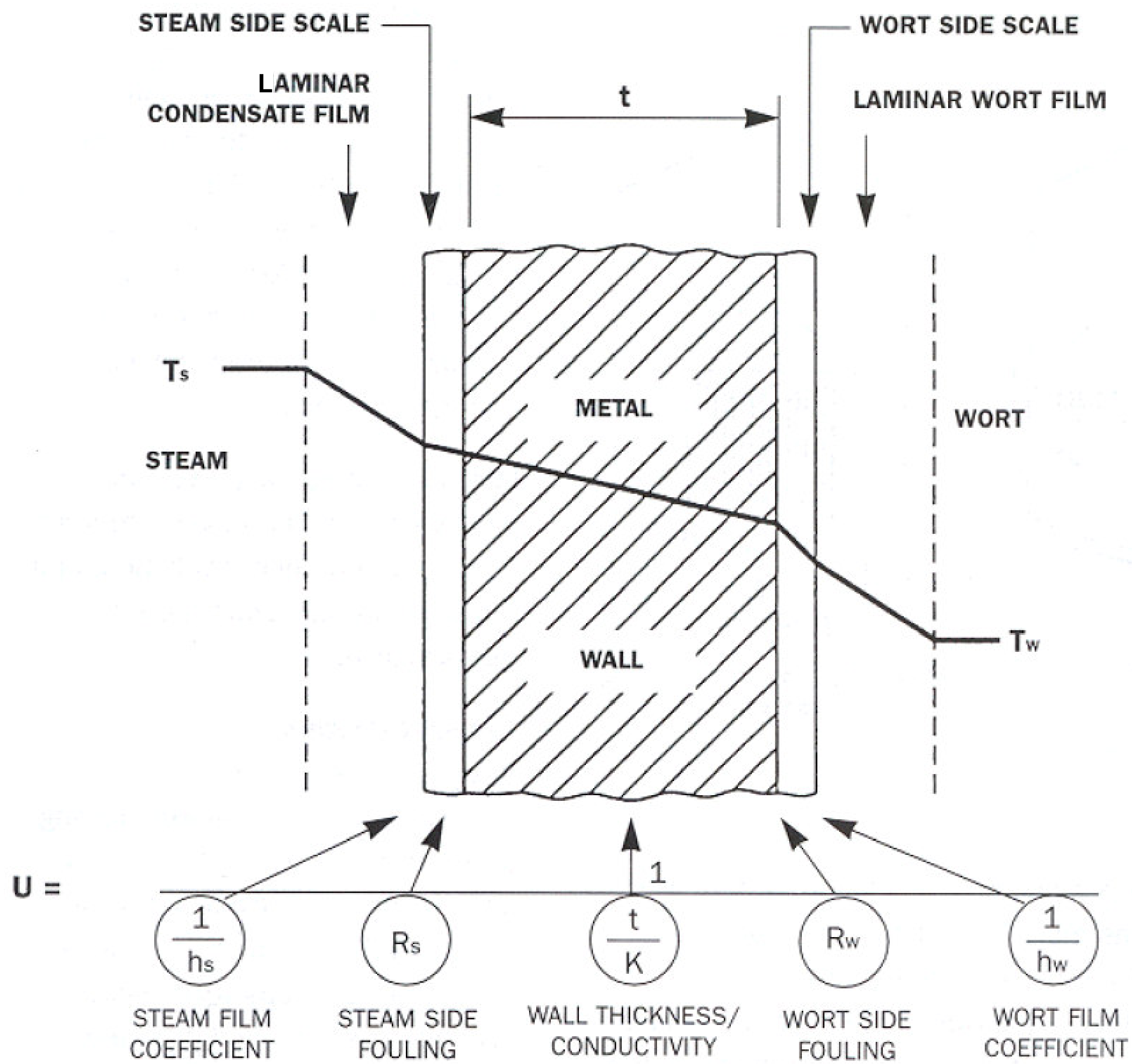
1) Protein Denaturation & Coagulation
2) Volatile Stripping
3) Hop Acid Isomerisation

<u>Intensity of Boil</u>

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



Heat Transfer Coefficient & Fouling



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Heat Transfer - Fouling, Area & ΔT

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

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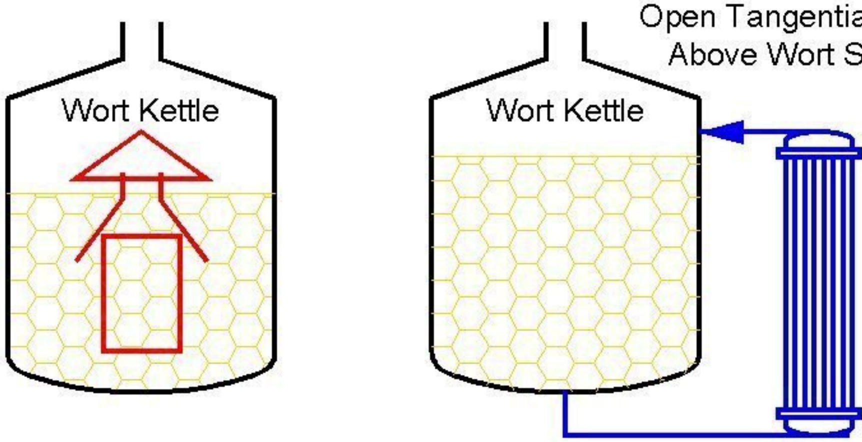
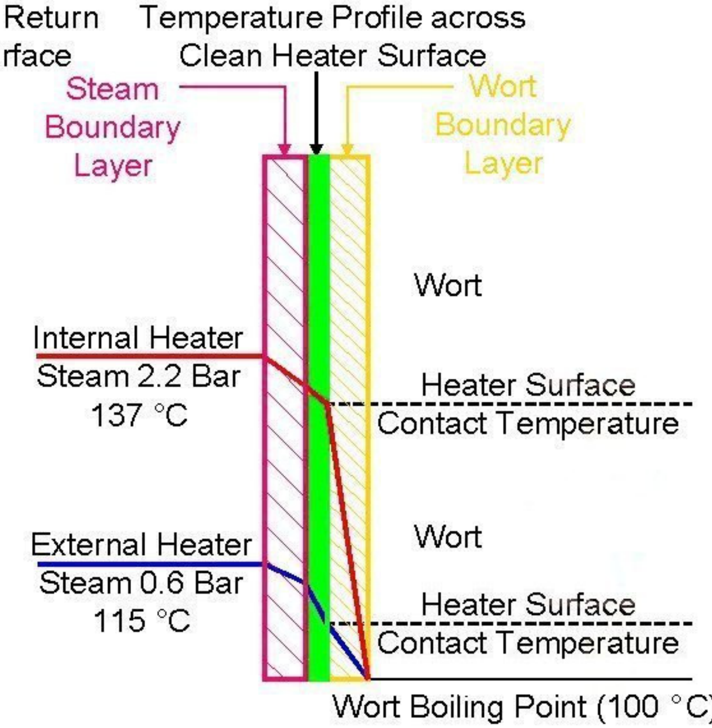
Wort Boiling Heat Transfer – Surface Area



Typical Internal Heater
Heater Surface Area
0.08 M^2 / HL

Typical British External
Thermosyphon
0.2 M^2 / HL



	Evap. Rate	Q = Rate of Heat Transfer	U x Heat Transfer Coefficient	A x Heater Surface Area	Delta T Steam / Wort Temperature Difference
	% / Hr	kW / Hl	kW / M^2 / °C	M^2 / Hl	°C
INTERNAL	7	4.63	1.57	0.08	37
EXTERNAL	7	4.63	1.57	0.20	15

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

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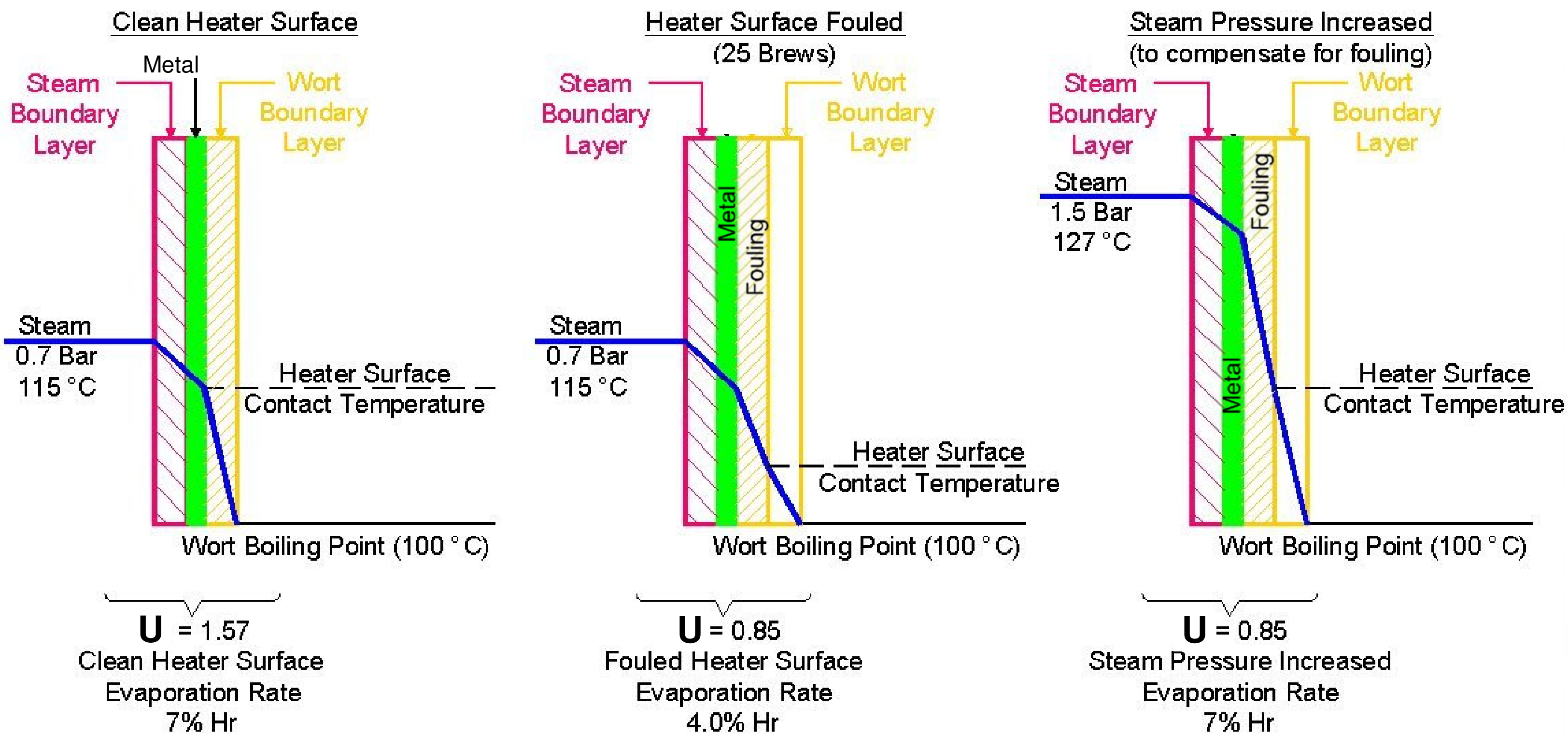
Wort Boiling Heat Transfer - Fouling



The larger external Heater will reach this degree of fouling after 25 brews, then needing 1.5 Bar steam @ 127 ºC. The smaller Internal Heater would reach the same degree of fouling after 10 brews. This would require 6.5 Bar Steam @ 168 ºC, 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.

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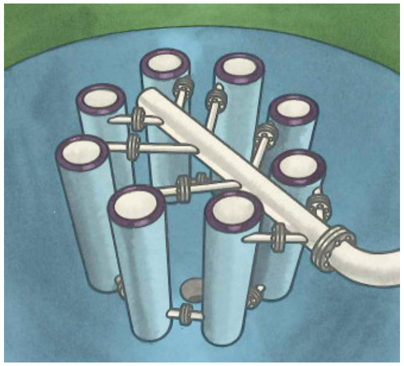
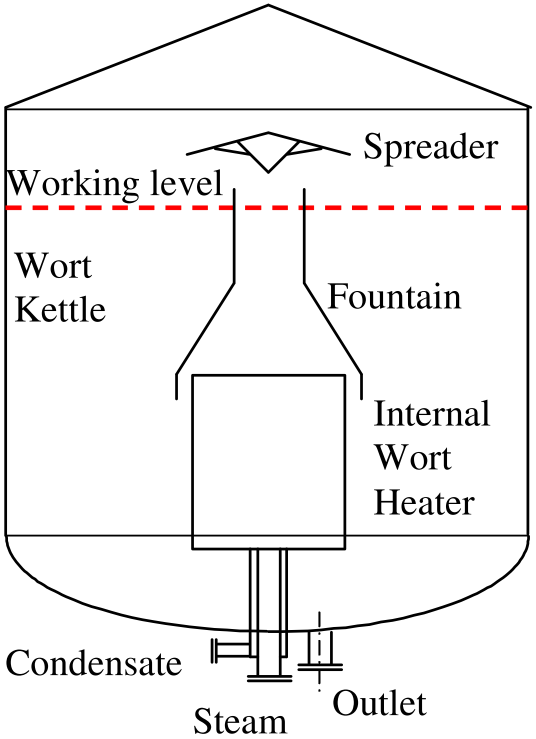
Wort Boiling Technology

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

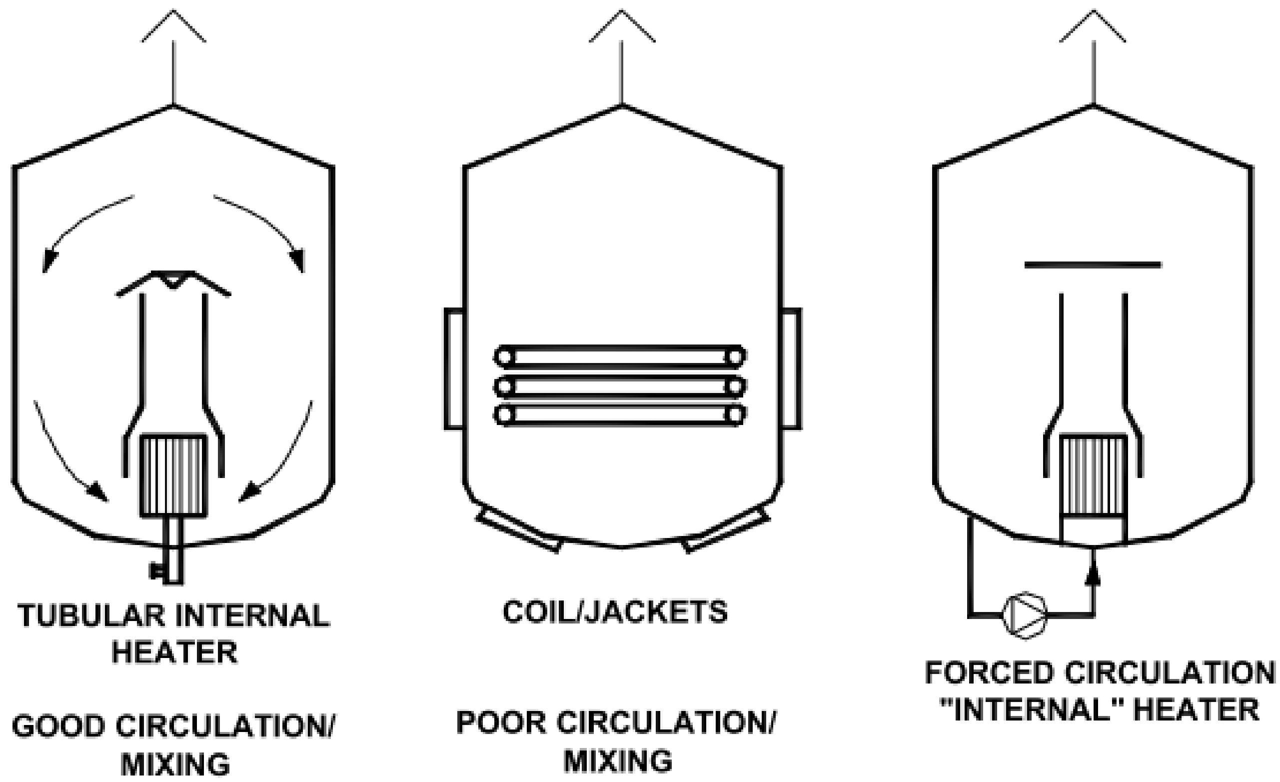
Internal Wort Heater

- Traditional
  - e.g. North America
- Percolators
  - Very low Surface area
- Tubular Internal Heater
  - Low Surface Area
    - Typically 0.08 m^2/hl
- Needs frequent CIP
- Fountain & Spreader
- May be pump assisted
  - Similar to External Heater



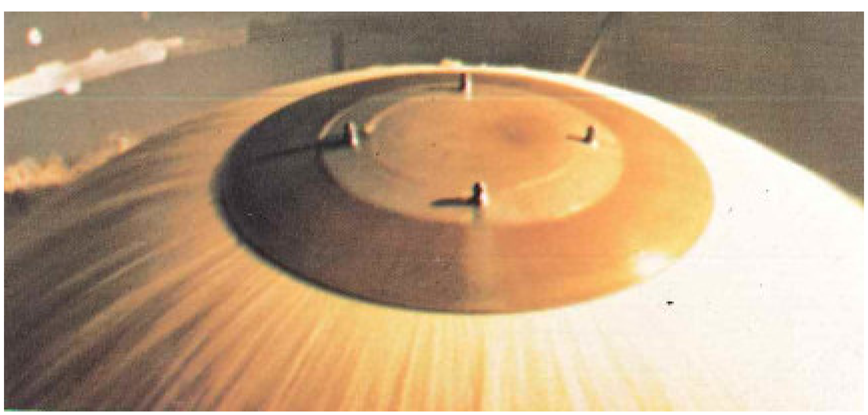


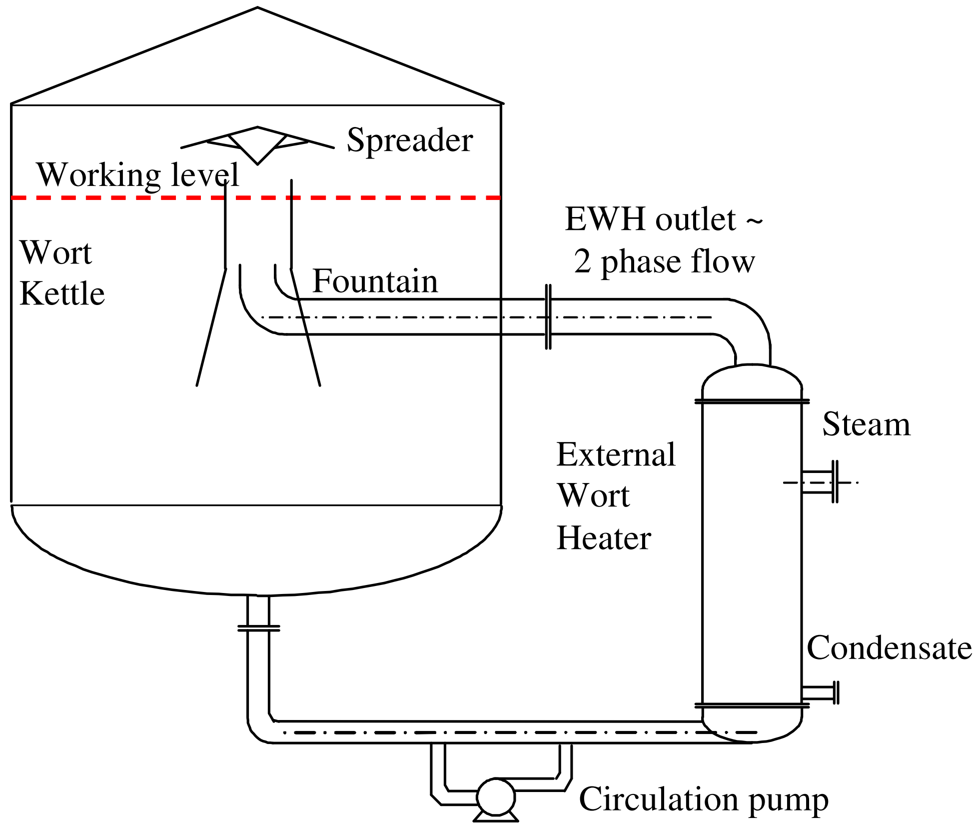
Internal Wort Heater - Technology



EWH – Fountain & Spreader

- Flexible
  - Brewlength
  - CIP volume
- Fountain & Spreader
- Thermosyphon
  - low shear
  - Typically 0.2 m^2/hl
- Or Forced Circulation
  - Pumped
  - high shear





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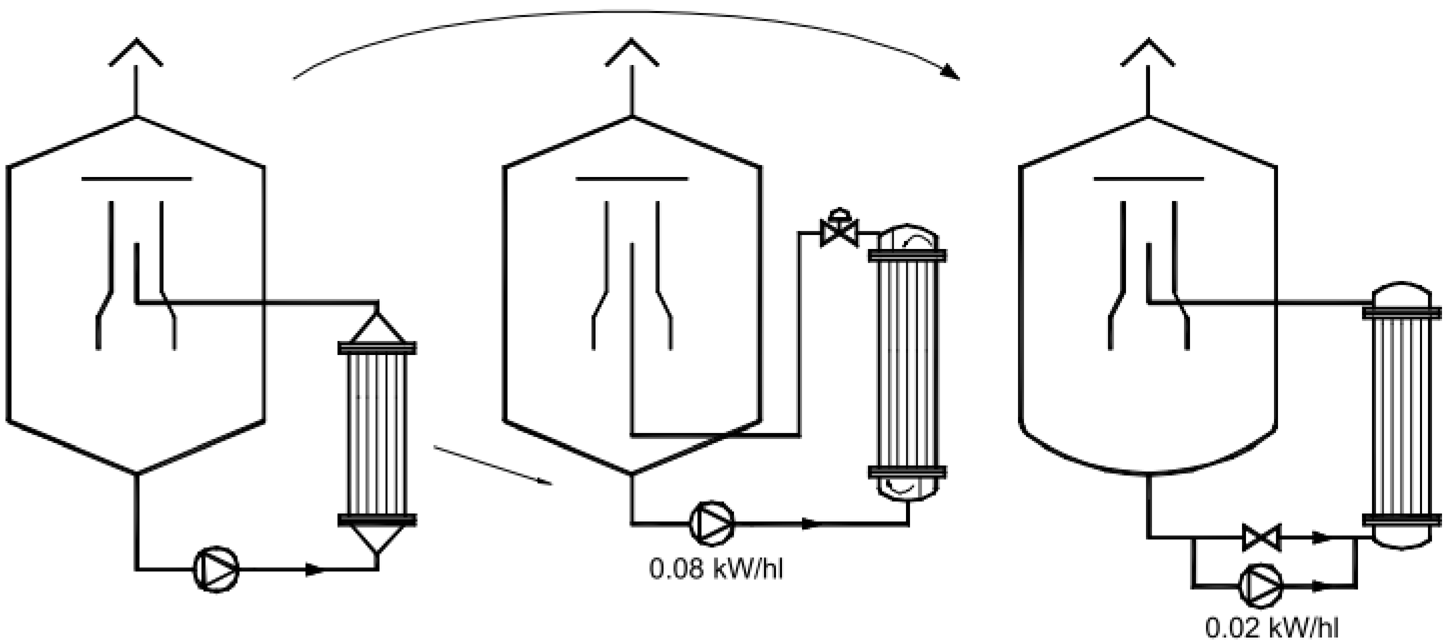
External Wort Heating Development



Original 1960's
Kalandria System

Pump Assisted
Circulation

Forced Circulation
3 Pass System
With Throttle Valve

Forced Convection
High Shear

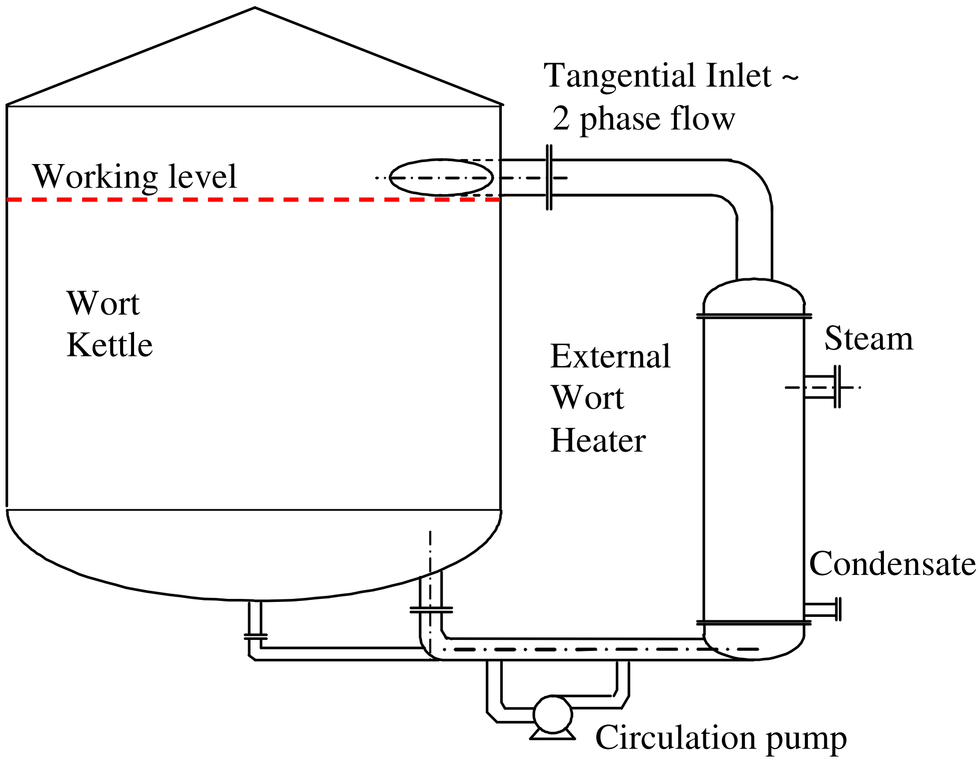
Thermosyphon
Kalandria System

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



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EWH – Symphony

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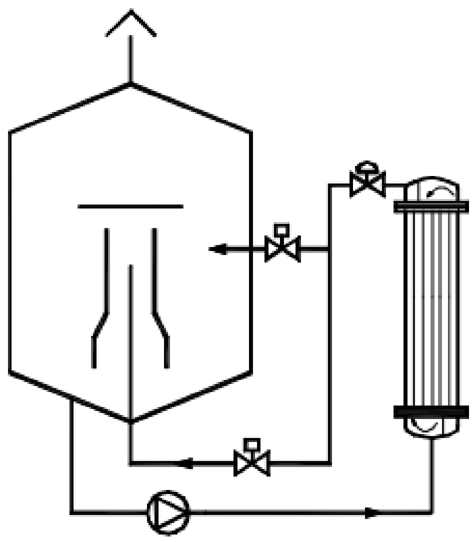
Kettle-Whirlpools

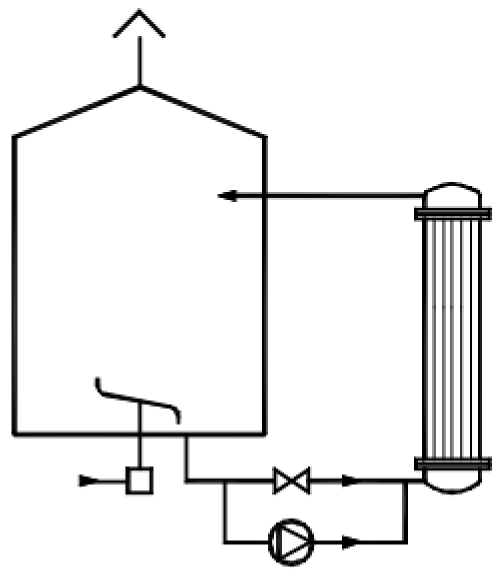
Combined Wort Boiling + Trub Separation

- Forced Circulation
  - High Shear



Forced Circulation
Seperate Boil &
Whirlpool Circulation

- Thermosyphon
  - 'Symphony Plus'



Thermosyphon
Boil & Whirl

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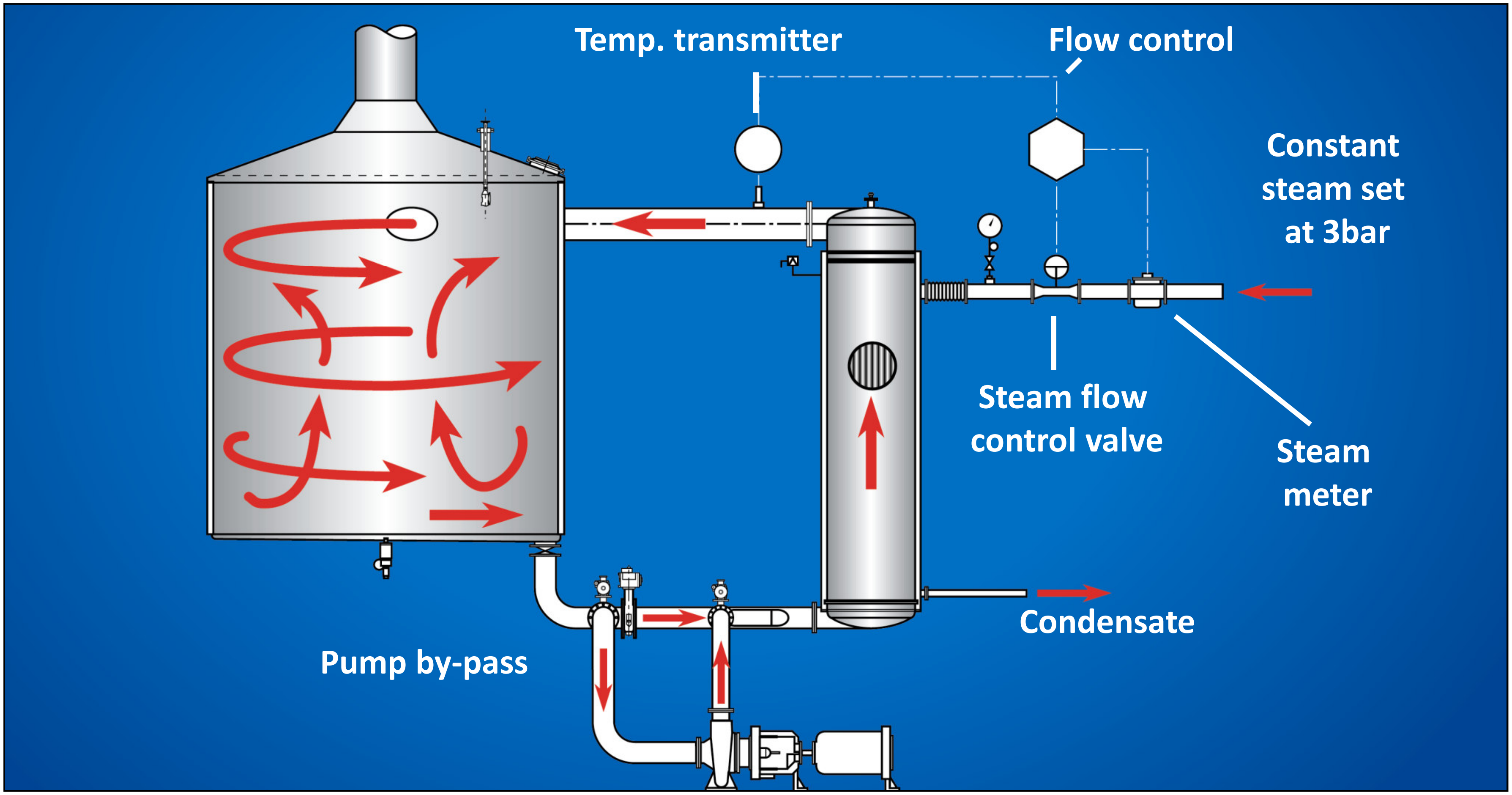
EWH – Symphony Plus

- Combined Kettle & Whirlpool
- Thermosyphon Circulation
- Eliminates Transfer to Whirlpool
- Reduced shear
- Improved Trub Separation

EWH – Symphony Plus



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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)

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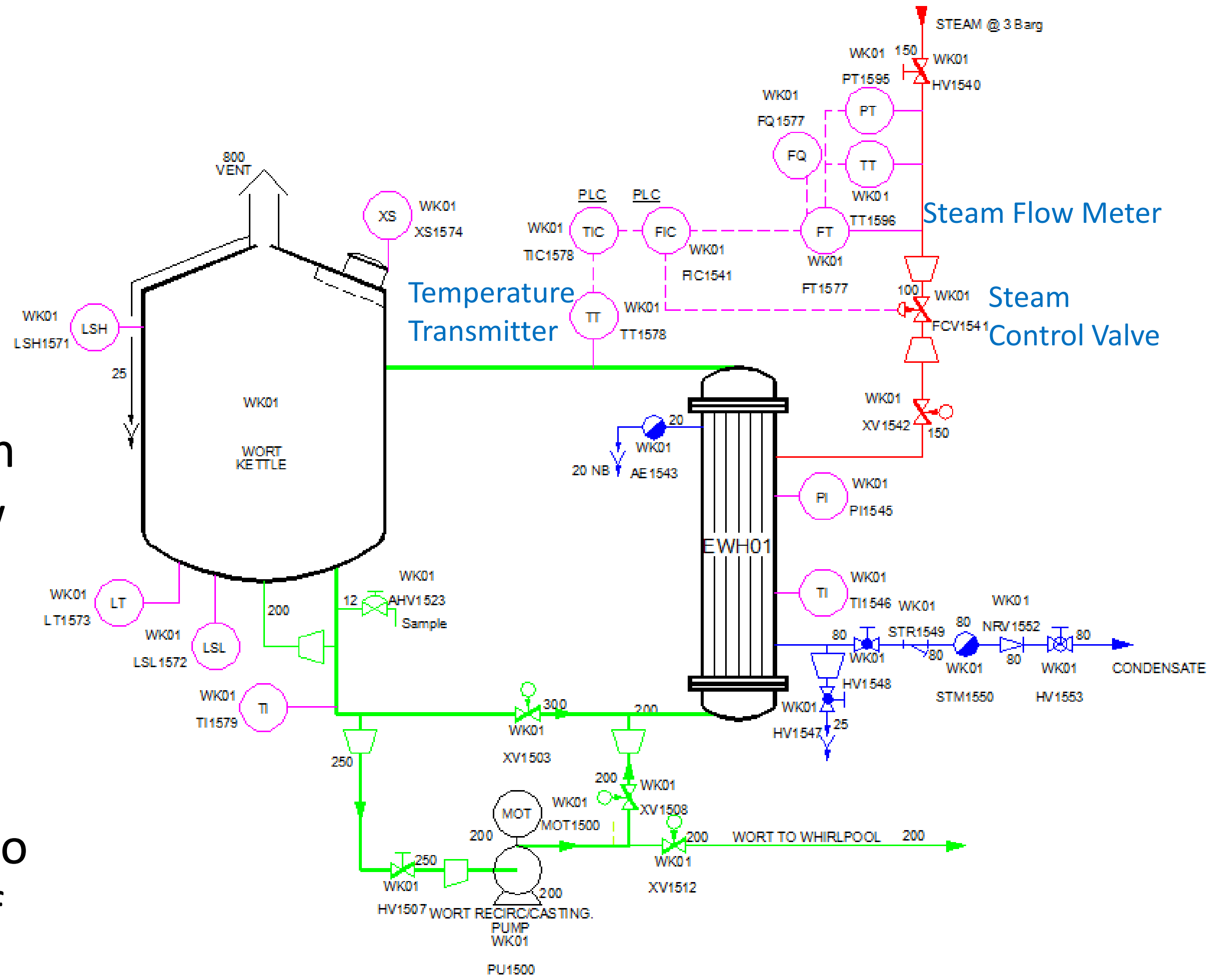
Wort Boiling Control

- 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.



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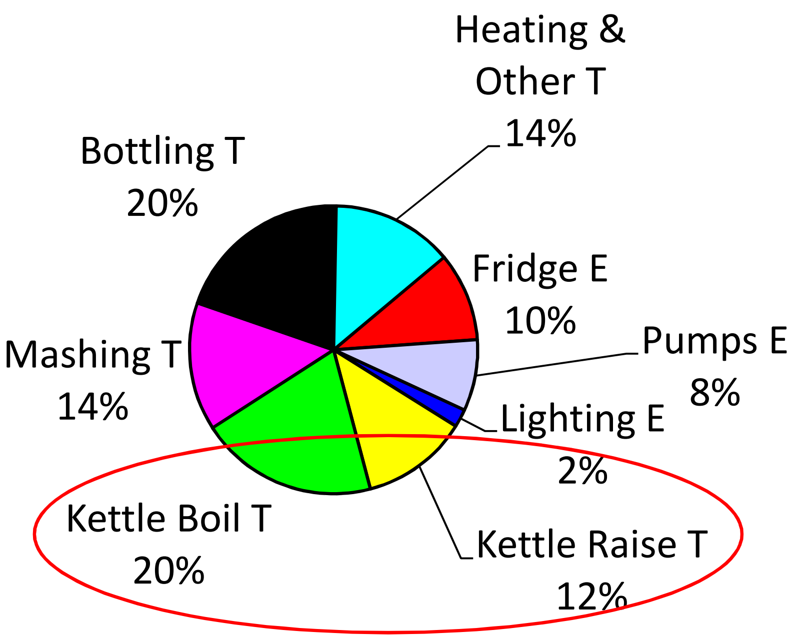
Wort Boiling - Energy Minimisation

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

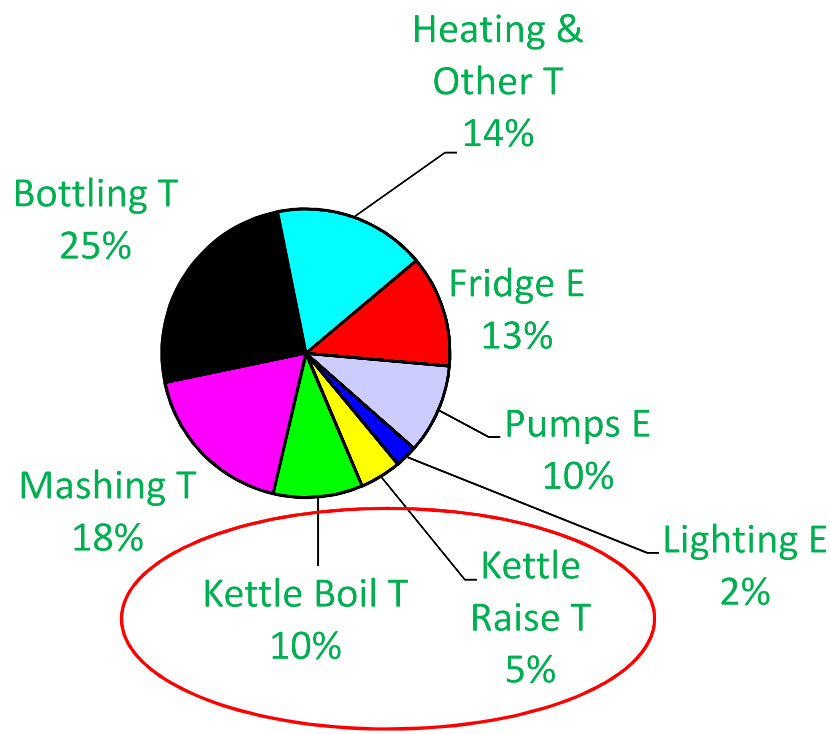
Wort Boiling - Energy Minimisation

Wort Boiling - Major Energy User

Historical data for a 10% Boil without Energy Recovery



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



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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

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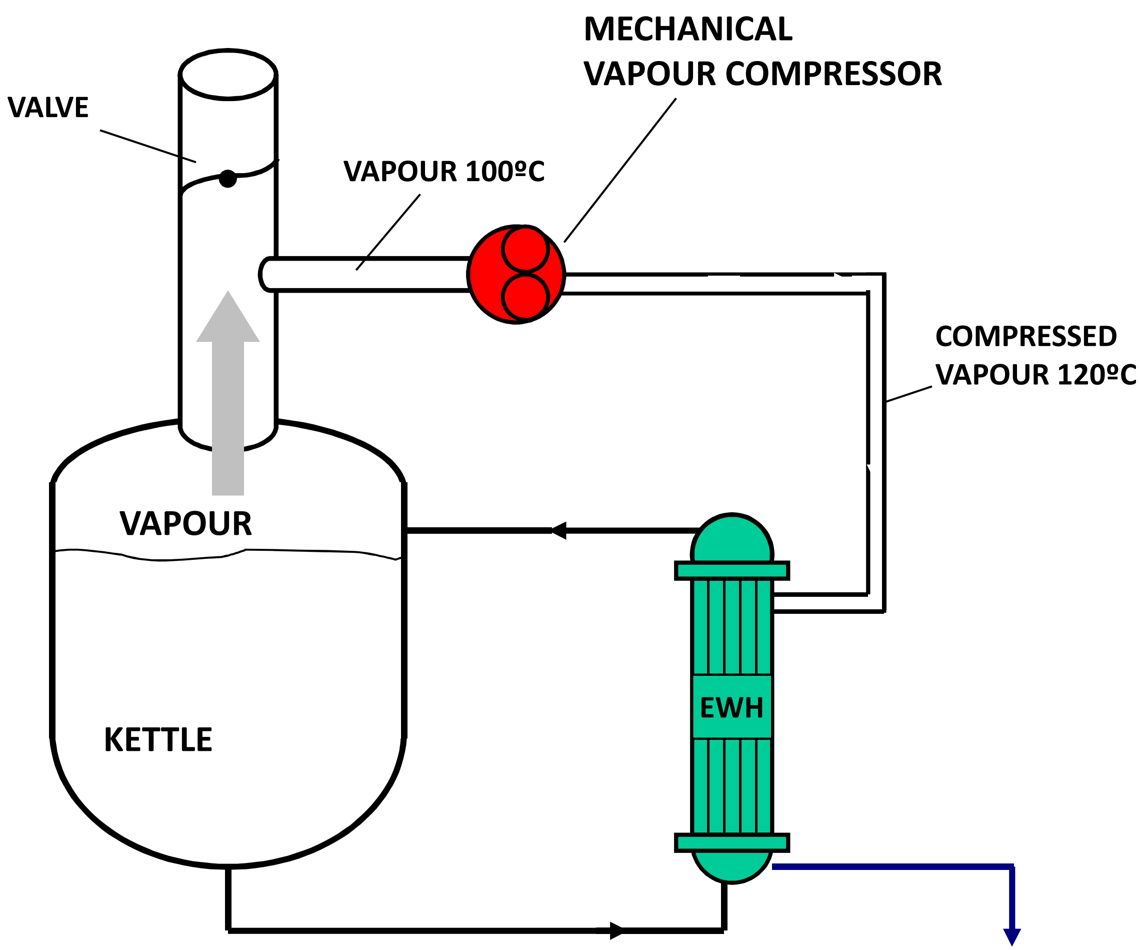
MVR – Mechanical Vapour Compression



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

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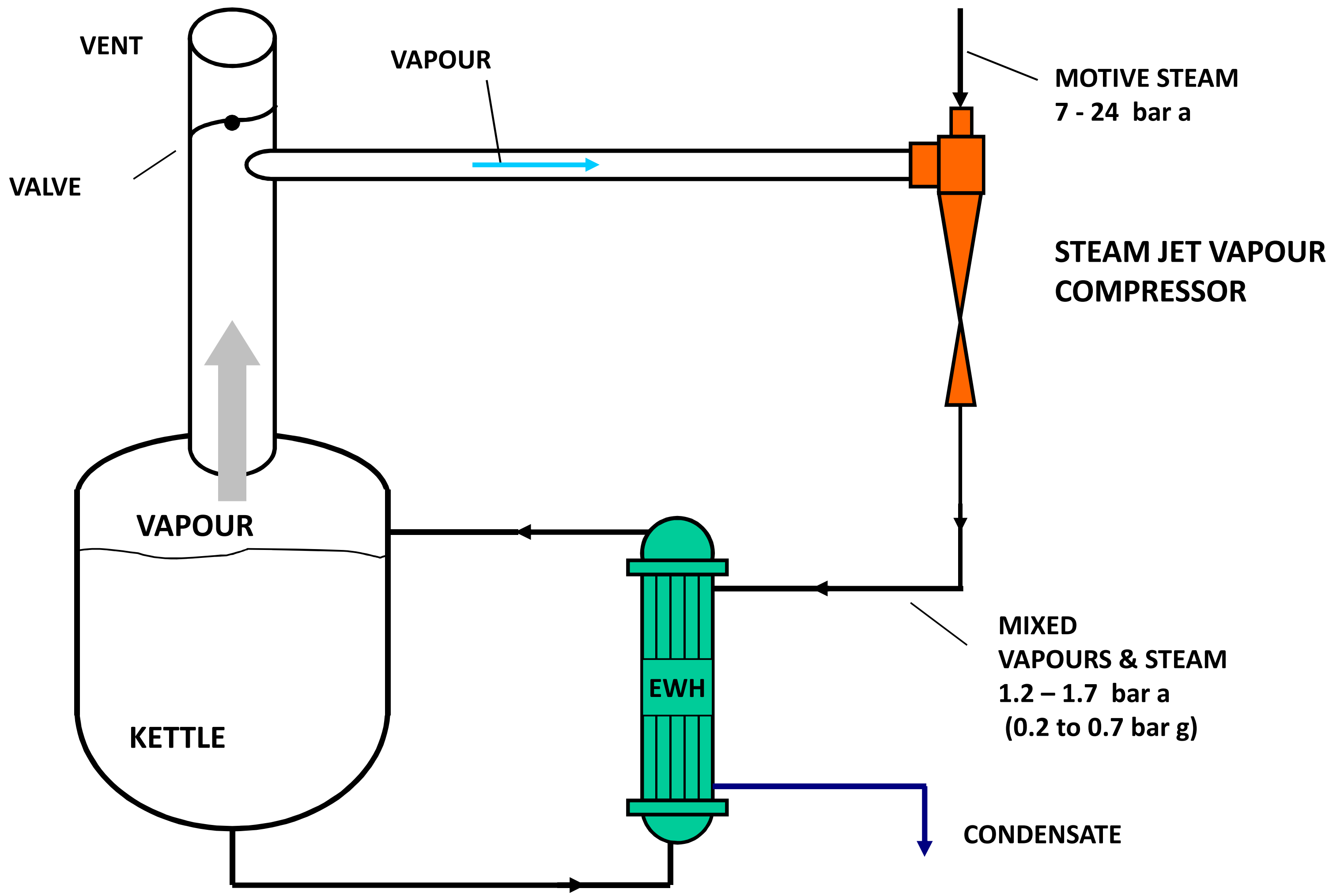
TVR – Thermal Vapour Compression



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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

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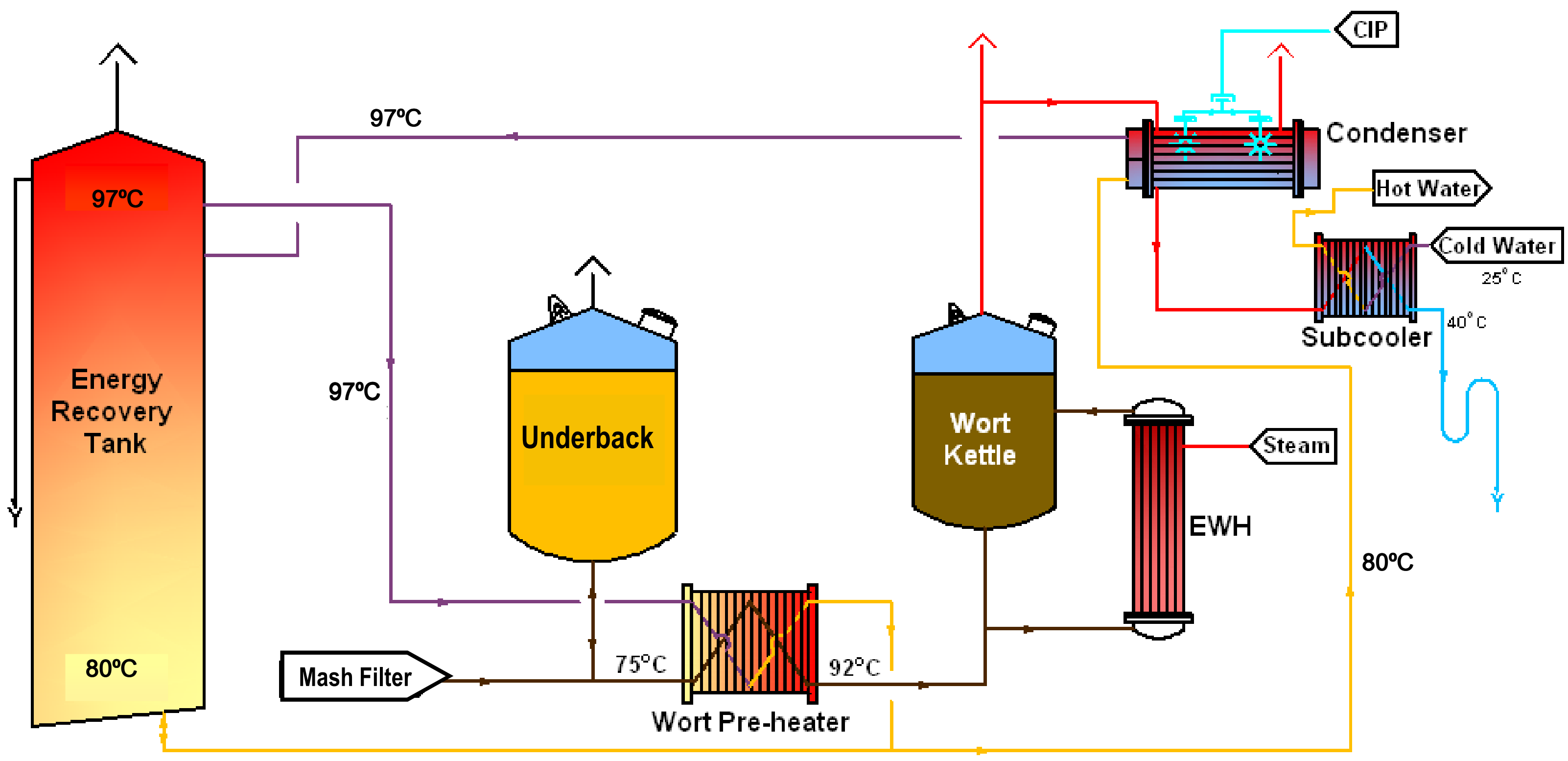
Energy Store – Wort Pre-heating



Energy Recovery System

Energy Store, Condenser & Pre-heater

Energy Store Tank

Condenser

Pre-heater

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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

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Energy Store – Wort Pre-heating Energy Reduction

- Heating Energy = M x C_P x (T_2 – T_1)
- <u>No Energy Recovery</u>
  - Heat 1000 hl wort – 75 to 100 °C

    = 100,000 x 4.0 x (100 – 75) = 10,000,000 kJ

    = 10,000 MJ
- <u>With Wort Pre-heating</u> to 92 °C
  - Heat 1000 hl wort – 92 to 100 °C

    = 100,000 x 4.0 x (100 – 92) = 3,200,000 kJ

    = 3,200 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

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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

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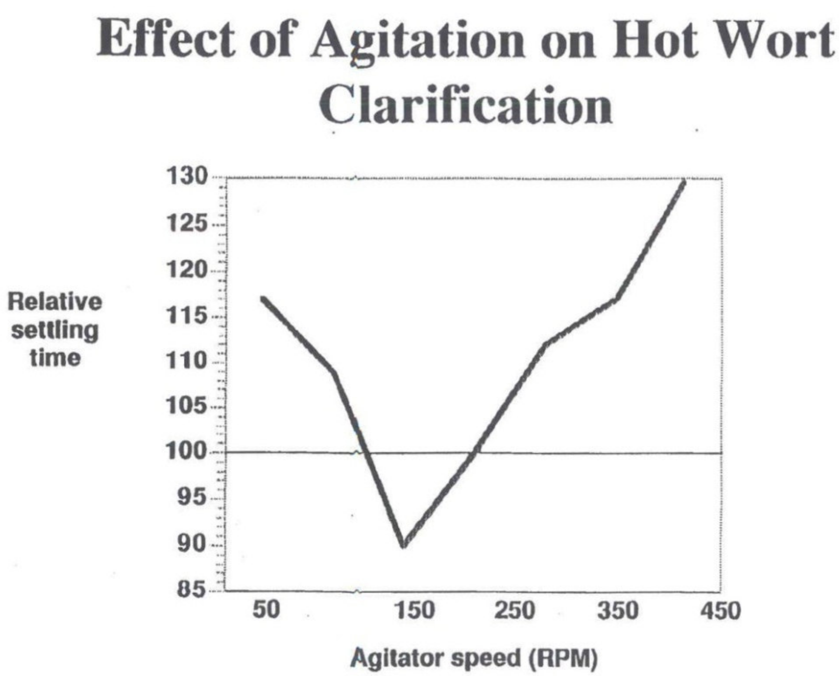
Hot Break & Cold Break vs Agitation



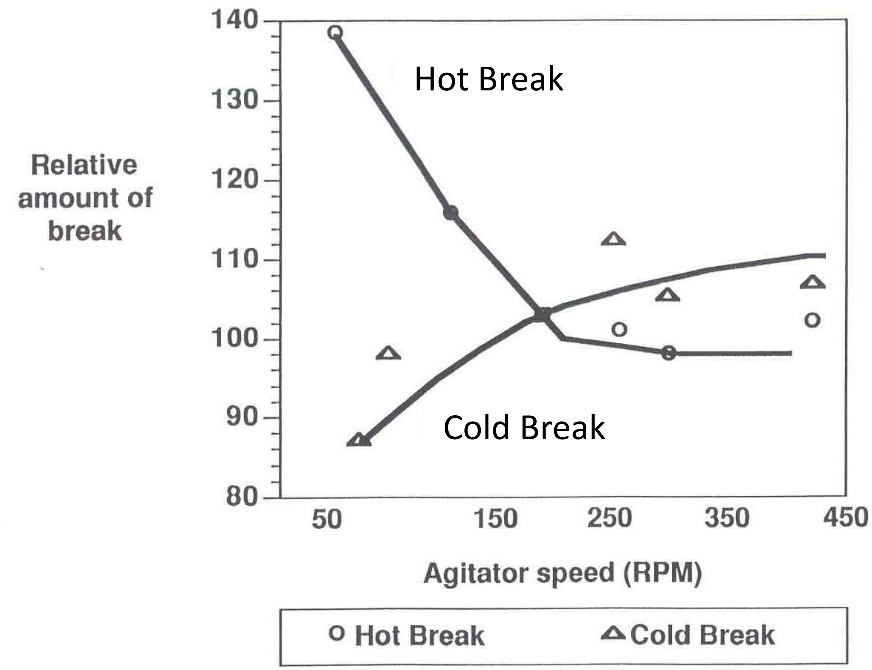
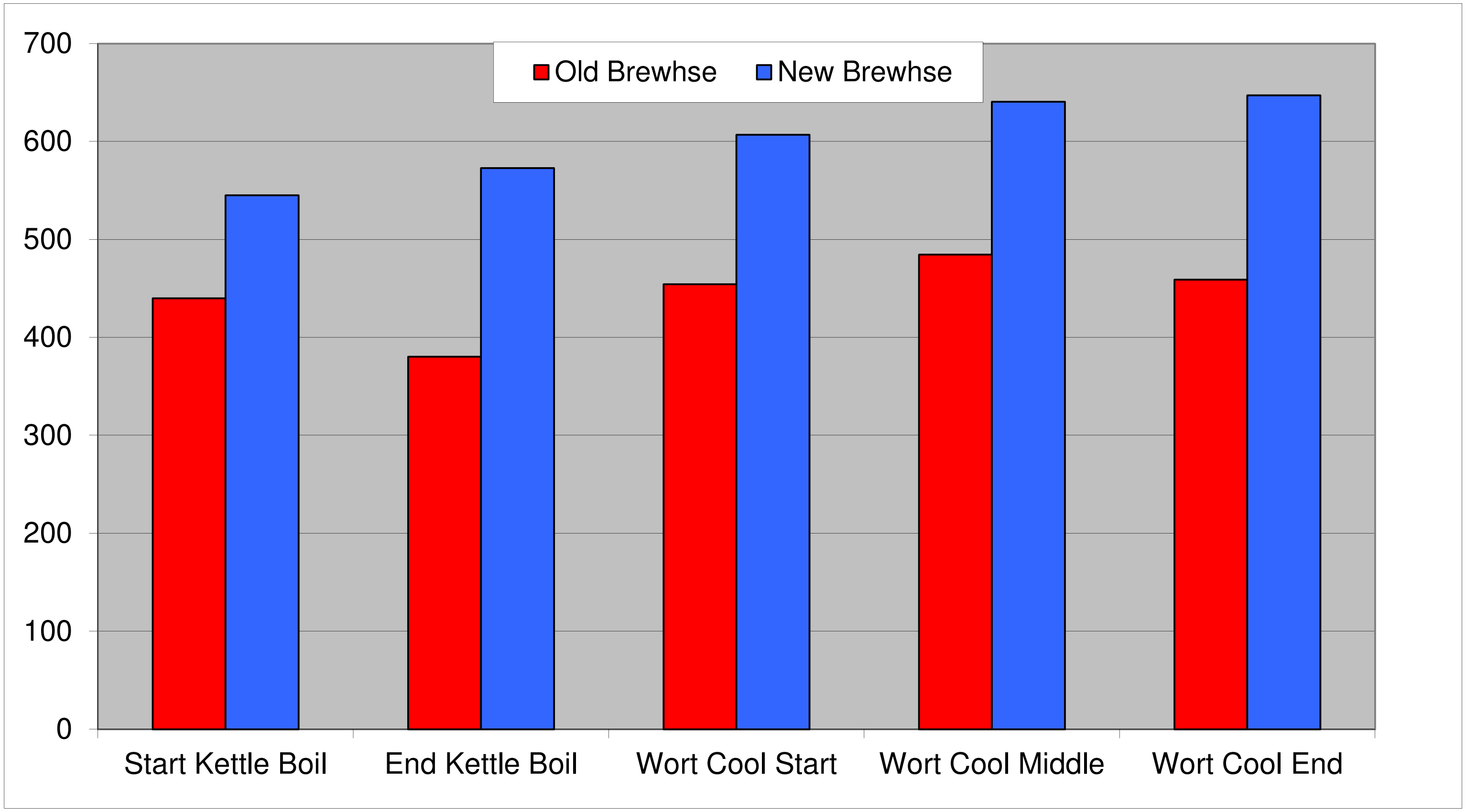


fig. 11 Effect of agitation on hot & cold break formation

- 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

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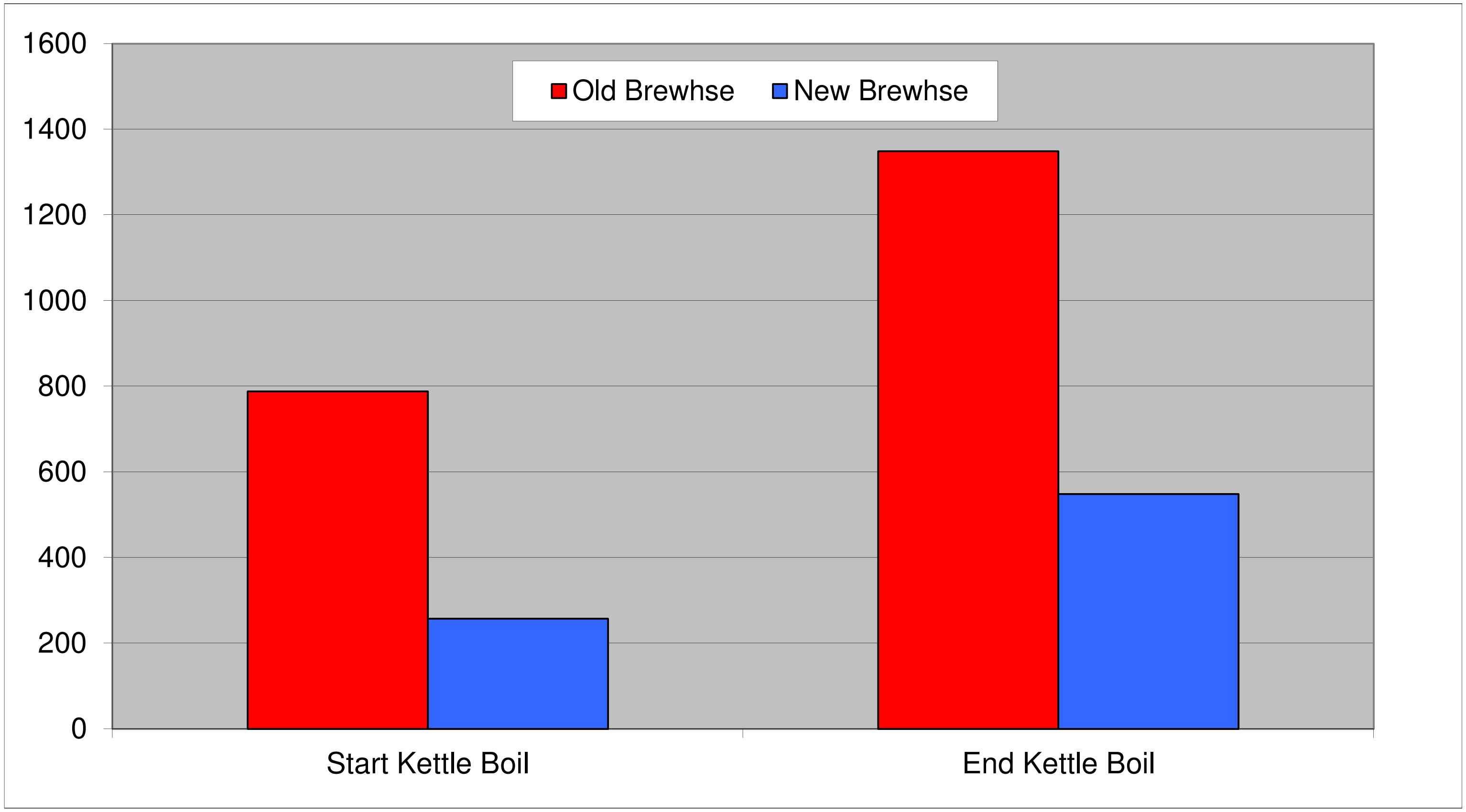
Reduction in Furfural levels



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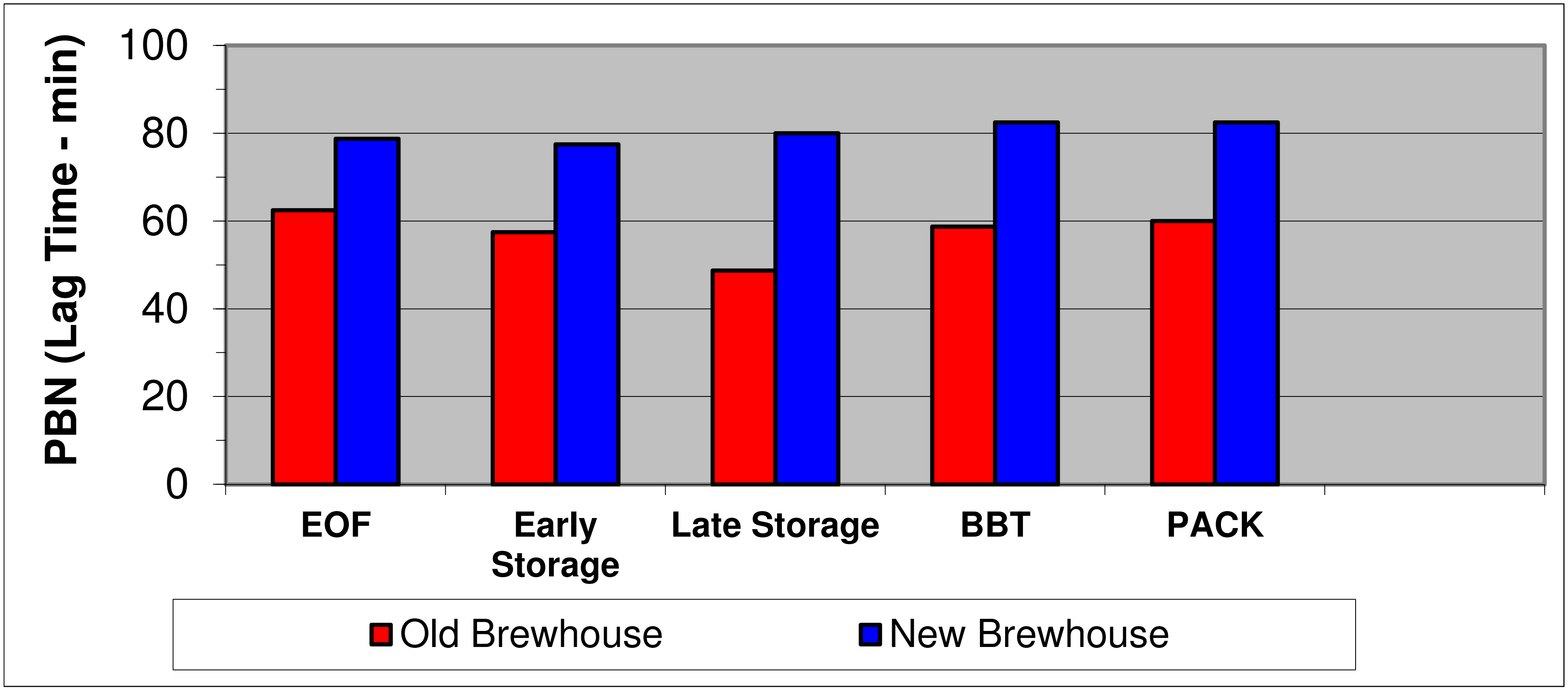
ESR Lag Time



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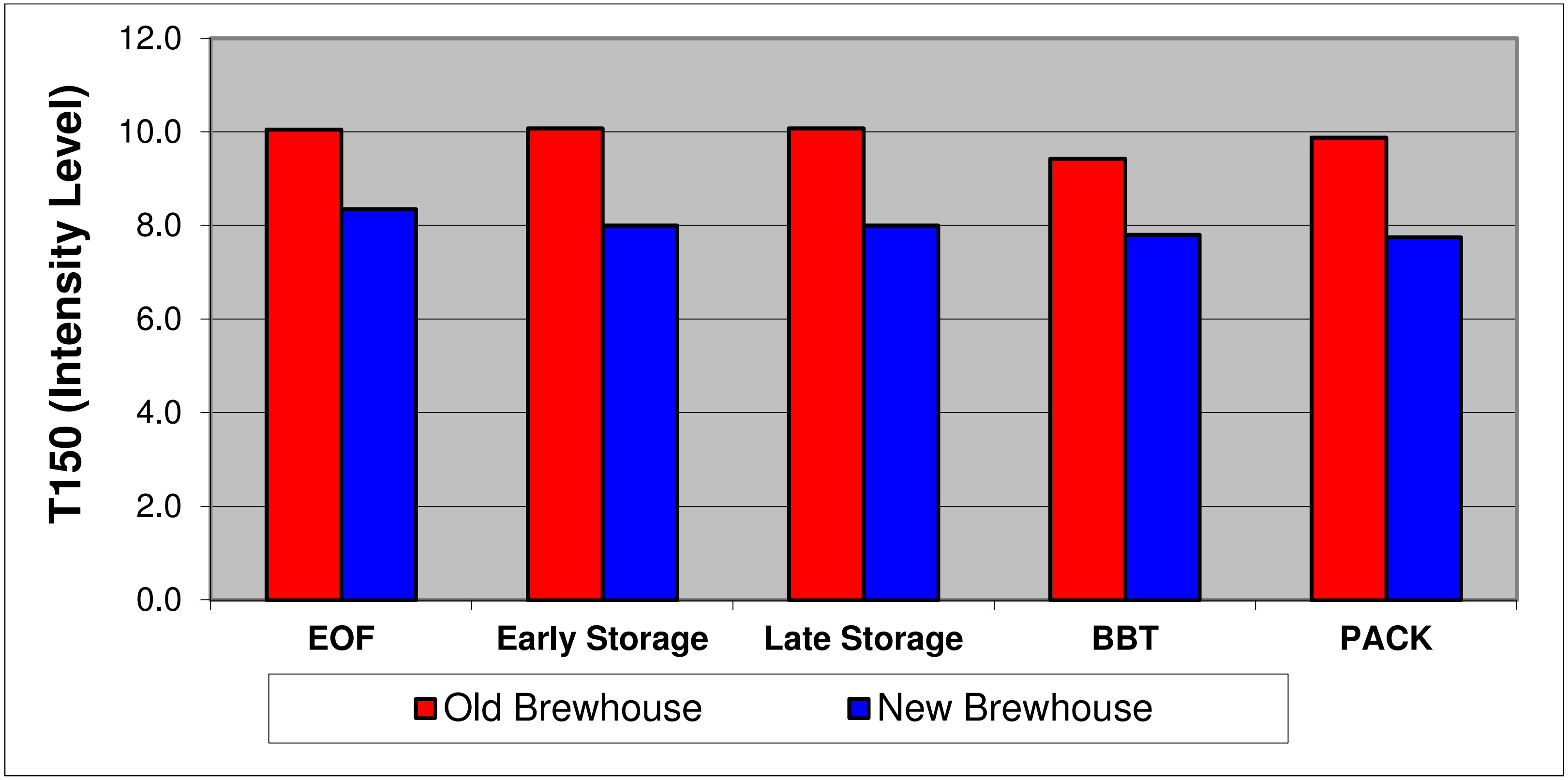
A - ESR T150



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