

How can we measure the product rate from a VM still?

Consider the Liebig product condenser. You have vapour coming in at some rate, measured in mass/sec; we'll use grams/sec. You have coolant (water) flowing at another rate of so many grams/sec. The vapour is condensing, giving up its Latent Heat of Vapourization (LHV) as it becomes a liquid, and this is heating up the coolant. Each gram (1/28 oz) of vapour heats 540 grams (19 oz) of coolant 1° C (1.8° F).

Start with the definition of a calorie: A calorie is the amount of heat needed to raise the temperature of one gram of water 1 degree Celsius (Centigrade).

$$\text{cal} = \text{Specific Heat} \times \text{mass} \times \Delta^{\circ}\text{C} \quad (1)$$

The Specific Heat (SH) is the relative amount of heat require to heat one gram of some substance one degree Celsius compared to water. For water the SH = 1cal/gram/°C because it is the reference material. 95%ABV ethanol has a SH of 0.601 cal/gram/°C = 0.601 cal/(gram × °C). The symbols $\Delta^{\circ}\text{C}$ means change in temperature in degrees Celsius. So, for example, if we heat up 15 grams of 95%ABV ethanol by 12°C, we would need $0.601 \text{ cal}/(\text{gram} \times ^{\circ}\text{C}) \times 15 \text{ grams} \times 12^{\circ}\text{C} = 108.2$ calories of heat.

The definition of Latent Heat of Vapourization for ethanol:

$$\text{cal} = \text{LHV}_{\text{ethanol}} \times \text{mass} = 220.8 \text{ cal/gram} \times \text{mass} \quad (2)$$

If you want to vapourize or condense 1 gram of ethanol, you will need 220.8 calories (the Latent Heat of Vapourization of ethanol); for 10 grams, you'll

need 2208 calories. The LHV is enormous compared to the SH (220.8 cal/gram vs. 0.601cal/gram/°C).

The ethanol vapour is coming into the Liebig at a constant *rate* and it is condensed to form a liquid flowing at a constant *rate*. We measure *rates* in so many things per second, so we can divide both sides of the equation by seconds:

$$\text{cal/sec} = (\text{LHV}_{\text{ethanol}} \times \text{mass})/\text{sec} \quad (3)$$

This is OK, because one of the fundamental axioms of algebra is that you can divide both sides of an equation by the same thing.

Now, $\text{cal/sec} = \text{SH}_{\text{water}} \times \text{mass} \times \Delta^{\circ}\text{C}/\text{sec}$ for the water coolant. Let's rearrange this into $\text{cal/sec} = \text{SH} \times \Delta^{\circ}\text{C} \times (\text{mass /sec})$, and mass/sec = flow rate (call it FR).

$$\text{So, } \text{SH}_{\text{water}} \times \text{mass} \times \Delta^{\circ}\text{C}/\text{sec} = \text{SH}_{\text{water}} \times (\text{mass/sec}) \times \Delta^{\circ}\text{C} = \text{LHV} \times \text{flow rate of vapour} = \text{LHV}_{\text{ethanol}} \times \text{FR}_{\text{ethanol}} \quad (4)$$

Remember, the symbols $\Delta^{\circ}\text{C}$ mean change in temperature measured in degrees Celsius.

$$\text{That is, } \text{SH}_{\text{water}} \times \text{flow rate of coolant} \times \Delta^{\circ}\text{C} = \text{LHV}_{\text{ethanol}} \times \text{FR}_{\text{ethanol}} = \text{cal/sec}$$

$$\text{Or, } \text{FR}_{\text{coolant}} \times \text{SH}_{\text{water}} \times \Delta^{\circ}\text{C} = \text{LHV}_{\text{ethanol}} \times \text{FR}_{\text{condensate}} \quad (5)$$

This means that if we know the flow rate of the coolant and the temperature difference of the input and output of the coolant of the Liebig condenser, and if we know that we are producing azeotrope ethanol, then we can calculate

the rate of ethanol production just by measuring the temperature difference across the Liebig coolant ports.

But wait a minute! The condensate is not coming out at 78.2°C, the temperature of the vapour. The Liebig is cooling it down so that it is tepid.

Therefore, there is even more heat going into the coolant. This heat rate is:

$$((78.2^{\circ}\text{C} - \text{temperature of condensate}) \times \text{Specific Heat of ethanol}) \times (\text{mass of ethanol} / \text{second}) = \text{cal/sec} \quad (6)$$

We can measure the liquid product temperature by adding another sensor to the output of the Liebig condenser.

Putting this all together gives:

$$\text{FR}_{\text{coolant}} \times \Delta^{\circ}\text{C}_{\text{coolant}} \times \text{SH}_{\text{water}} = (\text{LHV}_{\text{ethanol}} + \text{SH}_{\text{ethanol}} \times \Delta^{\circ}\text{C}_{\text{condensate}}) \times \text{FR}_{\text{condensate}} \quad (7)$$

Rearranging, the flow rate of the condensate is:

$$\text{FR}_{\text{condensate}} = \text{FR}_{\text{coolant}} \times \Delta^{\circ}\text{C}_{\text{coolant}} \times \text{SH}_{\text{water}} / (\text{LHV}_{\text{ethanol}} + \text{SH}_{\text{ethanol}} \times \Delta^{\circ}\text{C}_{\text{condensate}}) \quad (8)$$

Now $\text{SH}_{\text{water}} = 1 \text{ cal}/(\text{gram} \times ^{\circ}\text{C})$, $\text{LHV}_{\text{ethanol}} = 220.8 \text{ cal}/\text{gram}$,

$$\text{SH}_{\text{ethanol}} = 0.601 \text{ cal}/(\text{gram} \times ^{\circ}\text{C}),$$

Substituting:

$$\text{FR}_{\text{condensate}} = \text{FR}_{\text{coolant}} \times \Delta^{\circ}\text{C}_{\text{coolant}} \times \text{SH}_{\text{water}} / (220.8 + 0.601 \times (78.2^{\circ}\text{C} - \text{T}_{\text{condensate}})) \quad (9)$$

We have assumed flow rates in grams/sec. If you wanted grams/minute for the flow rates, or oz/min, all you have to do is measure the coolant flow rate in these units. The condensate flow rate will be in the same units.