CLL121 Coding Exercise: Design of an accumulator for steady boiler operation

Based on problem 6.55 of the textbook

6.55. The *total* steam demand of a plant over the period of an hour is 6,000 kg, but instantaneous demand fluctuates from 4,000 to 10,000 kg hr^{-1}. Steady boiler operation at 6,000 kg hr^{-1} is accommodated by inclusion of an *accumulator*, essentially a tank containing mostly saturated liquid water that "floats on the line" between the boiler and the plant. The boiler produces saturated steam at 1,000 kPa, and the plant operates with steam at 700 kPa. A control valve regulates the steam pressure upstream from the accumulator and a second control valve regulates the pressure downstream from the accumulator. When steam demand is less than boiler output, steam flows into and is largely condensed by liquid residing in the accumulator, in the process increasing the pressure to values greater than 700 kPa. When steam demand is greater than boiler output, water in the accumulator vaporizes and steam flows out, thus reducing the pressure to values less than 1,000 kPa. What accumulator volume is required for this service if no more that 95% of its volume should be occupied by liquid?

The design needs to be done for a specified period (Δt) of low steam demand. During this period, the increase in liquid volume fraction in the accumulator will be inversely related to the accumulator volume (V_{acc}). Another constraint determining V_{acc} is the requirement on accumulator pressure: $P_2 < P_{acc} < P_1$. Develop a code in language/library of your choice (C, Matlab, Python, etc.) to determine accumulator volume as per the problem statement given above for two separate scenarios.

1. (9 marks) The liquid volume fraction in the accumulator is a pre-specified parameter both in the initial (α_i) and in the final state (α_f). The solution approach for this part is given later in this file.
2. (3 marks) A more appropriate design will involve estimating minimum V_{acc} without fixing the liquid volume fraction in the final state. The upper limit on accumulator volume fraction ($\alpha_f = 0.95$) and the limits on accumulator pressure still need to be satisfied.

Code requirements and viva instructions

- All the parameter values listed in problem statement 6.55 (e.g., 95% liquid volume in final state, boiler operation at 6000 kg hr^{-1}, boiler pressure of 1000 kPa, etc.) should be defined as input parameters in your code to be specified by the user at time of execution. Their value should be supplied in an input file. 1 mark penalty if parameter values directly specified (hard coded) in code.
- Following constraints are applicable on various pressure values:
  - Boiler supply pressure (P_1) : 800 kPa $< P_1 <$ 1000 kPa
  - Plant supply pressure (P_2): 700 kPa $< P_2 <$ 750 kPa
  - Accumulator pressure (P_{acc}): $P_2 + 100 < P_{acc} < P_1 - 50$

The saturated steam data for above pressure range can be added directly to the code or be put in a file that is read in the code. Following data is available / determinable from the saturated steam table (see solution approach for more details):

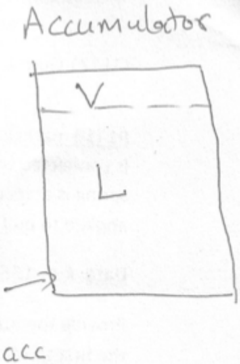
- Specific enthalpy at P_1 and P_2
- Specific volume and specific internal energy at initial and final accumulator pressure (P_i, P_f).

Notes

- Viva schedule will be announced later. It will be in last week of march.
- Appendix 1: Solution approach for part 1.
- Appendix 2: Test cases.
- Appendix 3: Steam table to be used for given assignment.
- Appendix 4: Additional information on steam accumulators.

APPENDIX 1

Final State:



$$M_f = \underbrace{\frac{0.95\, V_{acc}}{V_\ell^{sat}(P_f)}}_{m_{liq,f}} + \underbrace{\frac{0.05\, V_{acc}}{V_v^{sat}(P_f)}}_{m_{vap,f}}$$

final mass of (L+V) in accumulator

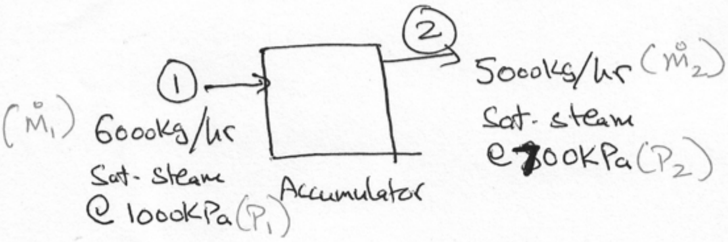
$$\equiv g_1(P_f, \alpha_f)\, V_{acc}$$

$$U_f^t = \left[\frac{0.95\, V_{acc}}{V_\ell^{sat}(P_f)}\right] U_\ell^{sat}(P_f) + \left[\frac{0.05\, V_{acc}}{V_v^{sat}(P_f)}\right] U_v^{sat}(P_f) \equiv m_{liq,f}\, U_\ell^{sat}(P_f) + m_{vap,f}\, U_v^{sat}(P_f)$$

final total int. energy of fluid in accumulator

$$\equiv g_2(P_f, \alpha_f)\, V_{acc}$$

Overall mass & energy balance:



Initial liq frac^n (volume) $\alpha_i = 0.90$

Final liq frac^n (volume) $\alpha_f = 0.95$

Mass balance: $m_f = m_i + (\dot{m}_1 - \dot{m}_2)\Delta t$

unsteady operation time

initial mass of (L+V) in accumulator

$$m_i = \underbrace{\frac{0.9\, V_{acc}}{V_\ell^{sat}(P_i)}}_{m_{liq,i}} + \underbrace{\frac{0.1\, V_{acc}}{V_v^{sat}(P_i)}}_{m_{vap,i}}$$

$$\equiv g_1(P_i, \alpha_i)\, V_{acc}$$

Rewrite: $m_f - m_i - \{(\dot{m}_1 - \dot{m}_2)\Delta t\} = 0 \quad -①$

Energy balance:

$$\cancel{m_f} \; U_f^t - U_i^t + \dot{m}_2 H_2 \Delta t - \dot{m}_1 H_1 \Delta t = 0 \quad \text{—(2)}$$

$$U_i^t = m_{liq,i} U_l^{sat}(P_i) + m_{vap,i} U_v^{sat}(P_i)$$
$$\equiv g_2(P_i, \alpha_i) V_{acc}$$

Given:

$P_1, P_2, \dot{m}_1, \dot{m}_2, \Delta t, P_i,$
α_i, α_f

Unknowns:

V_{acc} , P_f

Solve (1), (2) to determine V_{acc}, P_f

- Constraint:

$P_2 < P_f < P_1$ for operation

Approach:

Re-write eq 1, as: $V_{acc}\left[g_1(P_f, \alpha_f) - g_1(P_i; \alpha_i) \right]$
$$= (\dot{m}_1 - \dot{m}_2)\Delta t = a \quad -(3)$$

Re-write eq 2, as: $V_{acc}\left[g_2(P_f, \alpha_f) - g_2(P_i, \alpha_i) \right]$
$$= \dot{m}_1 H_1 \Delta t - \dot{m}_2 H_2 \Delta t = b \quad -(4)$$

Divide to eliminate V_{acc}:

$$\boxed{\frac{g_2(P_f, \alpha_f) - g_2(P_i, \alpha_i)}{g_1(P_f, \alpha_f) - g_1(P_i, \alpha_i)} = \frac{b}{a}} \quad -(5)$$

- Solve for P_f
- use (3) or (4) to determine V_{acc}

Appendix 2: Test Cases

- Part 1: Both α_i and α_f specified.

- Input set 1: Solutions exists, i.e., $P_2 < P_f < P_1$

Input	
P_1 (kPa)	1000
P_2 (kPa)	700
$\dot{m}_1$ (kg/hr)	6000
$\dot{m}_2$ (kg/hr)	5000
Δt (hours)	0.5
P_i (kPa)	800
α_i	0.94
α_f	0.95

Function values (to facilitating intermediate checks on the code):

$g_1(P_i, \alpha_i)$	854.79
$g_2(P_i, \alpha_i)$	615278.59

a	500
b	1422500

Solution:

$P_f = 903\ kPa;\ V_{\text{acc}} = 55.1\ \text{m}^3$

Note: You might not get exactly same value as it will depend on the convergence criterion used.

Input set 2: No valid solution

Parameters: All values same as set 1, except, $\alpha_i = 0.92$

No physically valid solution obtained. The final accumulator pressure, P_f, needs to be greater than 1000 kPa.

- Part 2: Only α_i specified, and minimum V_{acc} to be determined (subject to other constraints)

Parameters: All values same as set 1, except, $\alpha_i = 0.92$ and α_f not fixed.

Solution:

$P_f = P_1 - 50 = 950\ kPa$

- one can deduct from the result of input set 2 that this highest possible P_f will give minimum V_{acc} for given parameters.

$\alpha_f = 0.9343;\ \text{V}_{\text{acc}} = 38.5\ \text{m}^3$

Appendix 3: Steam Table

Wednesday, 2 March 2022 10:05 AM

Steam table						
P(kPa)	Ul(kj/kg)	Uv(kj/kg)	Vl(m3/kg)	Vv(m3/kg)	Hl(kj/kg)	Hv(kj/kg)
700	696.33	2570.9	0.0011	0.273	697.1	2762
750	708.475	2573.75	0.0011	0.255	709.3	2765
800	720.02	2576	0.0011	0.24	720.9	2768
850	731.065	2575.35	0.0011	0.229	732	2770
900	741.61	2578.5	0.0011	0.215	742.6	2772
950	751.755	2580.2	0.0011	0.204	752.8	2774
1000	761.5	2582	0.0011	0.194	762.6	2776

- Use linear interpolation between nearest pressure values to get properties at a given P.

Importance of Steam Accumulator in Boilers

Posted on *August 29, 2019*

Steam Accumulator

Steam Accumulator is a shell type **pressure vessel** which is used to store **steam generated** by a **boiler** and use it for varying load demands.

Steam Boilers are generally designed for a certain capacity at which they could supply steam continuously which is also it is maximum continuous rating.

Know More: What is the boiler

So, the **steam boiler** designed for higher steam requirements can be made to run on lower loads or lower steam demands but a **boiler** designed for lower loads cannot run on higher loads or higher steam demands.

Generally, it is observed that the steam requirement in a process is not fixed and keeps changing with time. For some time period, there might be lower load requirements than the **steam boiler capacity** while for some period of time there might be high load requirements.

Low load requirements can be easily met by the boiler but high steam requirements cannot be met by this **boiler** as it is not designed for such capacity. This is where a **steam accumulator** plays an important role as they store steam generated by the boiler and use it as and when required.

Steam Accumulators are designed in such a way that when there is an excess of steam, that when lower loads are required than the **boiler maximum load**, the excess **steam gets stored** in an accumulator and when the process **steam load requirement increases**, the steam from both the boiler and the **accumulator** can be released to meet up the **process requirement**.

Installing a **steam accumulator** would bring about a huge reduction in **boiler size**, thereby reducing the cost of a **boiler**, **installation cost**, operating cost and increased boiler efficiencies.

Steam Accumulator as the cost-effective solution

- The plant already having a boiler of a certain capacity but for some reasons, the process load requirement increases for certain time period in a day while for other time, process load requirement falls even below the maximum capacity.
- Plant planning to install a **boiler** for their process must consider the average heat load requirement of their process for deciding the maximum boiler capacity, and for the overload conditions, the steam accumulator can be installed.

Deciding the capacity of the ***steam accumulator*** is not an easy task as it requires full time monitoring the steam flow rates in a process and making an organized chart showing the excess **steam generation** and overload steam demand.

This data is collected for at least 2 to 3 days and any other load variations are recorded. Then this data helps in calculating the maximum capacity of a **Steam Accumulator**.

We, at **Thermodyne Boilers**, have manufactured, supplied and commissioned **Steam Accumulators** to many of our Clients. And their continuous operation with time has ensured the reliability that we consistently work upon.

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Why You Need Steam Accumulators

Posted on *July 21, 2019*

Steam accumulators is a pressure tank that is coated with steel for the purposes of holding steam under high pressure. Purpose of the **steam accumulators** *is to release steam at the time when the demand for the steam is greater than the ability of the boiler to supply the amount required and when the demand is low, it helps to accept the steam back, To meet fluctuating & sudden steam load & To meet peak load demands in specific industries*

Steam Accumulator

How steam accumulator charges the steam: the tank is filled halfway with cold water then a steam is blown into the tank from **a Steam Boiler** through perforated pipes that are attached along the base of the tank. in the event that the **steam accumulator** has charged to its fullest, some of the heated water will then condense back to the tank and as a result, it raises the levels of water in the tank to almost full and in the process, the pressure and even temperature go up in the tank.

How **steam accumulator** discharges the steam: the amount of steam in the tank can be drawn out any time depending on the need, for example, it can be drawn either for the purposes of driving **steam turbines** or for processing purposes through a steam valve located at the top of the tank.

Also, read *– Importance of Steam Accumulator in Boilers*

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