International Compressor Engineering Conference

School of Mechanical Engineering

2022

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Rane, Milind V; Jha, Arun M; and Rane, Adittya M, "Near Isothermal Steam Compressor for Jaggery Making" (2022). *International Compressor Engineering Conference.* Paper 2781.
https://docs.lib.purdue.edu/icec/2781

Near Isothermal Steam Compressor for Jaggery Making

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ABSTRACT

The sugar industry is 2nd largest agro-based industry in India. Sugarcane farmers can realize higher returns if efficient jaggery-making options are available. Almost 36% of sweetener requirement is fulfilled by jaggery in India. Traditional jaggery making is less energy-efficient and often uses undesirable chemicals to improve the colour of jaggery. The entire bagasse needs to be fired. Scraping juice in boiling pans is laborious and stressful. Workers experience severe heat stress because of exposure to smoke and hot environment. Hot spots formed in pans cause inversion of sugar, and browning of jaggery which reduces the price realised. Improvement in the jaggery production process and the quality of jaggery produced can significantly enhance the livelihood of sugarcane producers. As the juice concentration progresses, boiling point elevation increases from 0.56ºC at 20 ºBrix to 18ºC at 90ºBrix. This leads to a reduction in heat transfer coefficient which coupled to the heat transfer approach makes it extremely difficult to concentrate juice at jaggery conditions.

The paper presents a review of the conventional jaggery making process and design energy-efficient steam compressor to operate a tabletop Energy Efficient Jaggery Maker (EEJM) based on Vapour Recompression System (VRS). Bagasse firing is eliminated, so the bagasse can be used for other applications like mushroom cultivation, composting, biogas generation, paper making, etc. VRS enables recycling of heat by compressing the vapour generated from the juice concentration process. The condensed water vapour can also be used as pure water for various applications.

1. INTRODUCTION

India is the world's second-largest producer and biggest consumer of sweeteners. The Sugar industry is the second largest agro-based industry in India after the cotton textile industry. Maharashtra has one-fourth of the total sugar mills and produces almost one-third of the total sugar produced in India. This industry involves a total capital investment of almost 125 Million INR (16.3×10^7 USD) and employs approximately 0.286 Million workers. Moreover, 25 Million sugarcane growers also get benefit from this industry. This helps to strengthen the socio-economics of rural India. Although there is great cultural diversity in India, jaggery is used in eatables in almost all regions. Almost 50% of jaggery production in the world is from India. It is the traditional sweetener used across the country. It is also preferred for consumption due to its medicinal value. Jaggery is conventionally prepared by evaporation of water for the concentration of sugarcane juice in an open pan boiling which has a low thermal efficiency of 35 to 45%. Furnace heat utilization efficiency is very low, which is ~15% for single, ~30% for two, and 50 to 60% for four pans (Rane and Uphade, 2017).

The current jaggery-making process is highly labour intensive with harsh working conditions due to severe heat stress generated by open pan boiling. This limits the availability of labour thus hampering the overall process as well as product quality. Hot spots are formed due to high-temperature pool boiling of sugarcane juice in mild steel or stainless steel pan. It causes caramelisation of sugar and gives dark brown colour to jaggery which is considered by customers to be of inferior quality. The conventional Jaggery Making Process with open pan boiling is illustrated in Figure 1.

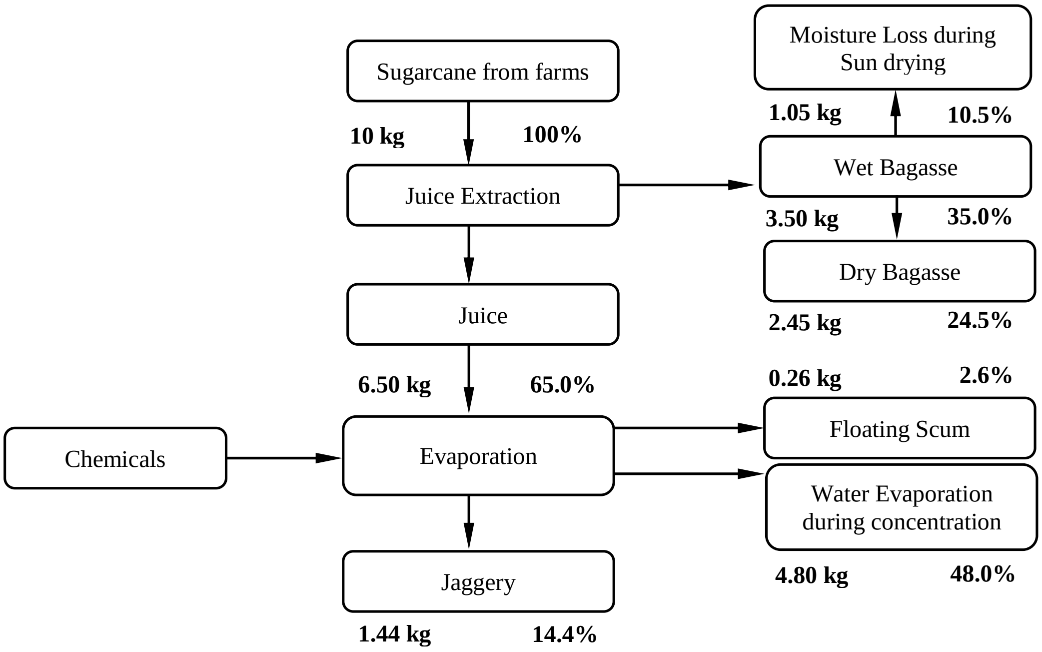

Figure 1: Conventional Jaggery Making Process

Also, the chemicals used for clarification of juice such as lime, sodium hydroxide, phosphoric acid etc. could pose health hazards to consumers which could be eliminated by enhancing the process. These process improvements would also lead to the saving of bagasse, a residue of the sugarcane juice extraction process, which can have other applications. Owing to this, saved bagasse can be used as fuel or as compost on farms, thus, improving the overall process efficiency.

It is evident from above that this industry generates revenue for the farmers and provides sustainable employment to rural people who would otherwise migrate to urban areas for livelihood. However, sub-optimal processes and technologies involved in the production of jaggery have impaired their growth. Thus, it can be said that the benefits of improving age-old inefficient processes are multifold. It will not only create better working conditions for factory labourers but also generate more revenue for the manufacturers as the quality of products gets improved. Additionally, saved bagasse and by-products like potable water allows it to more lucrative option.

This paper reports the development of a near-isothermal steam compressor for integration with a small-capacity tabletop jaggery maker. This paper also reports the theoretical performance of the Vapour Recompression System for jaggery making, which addresses the issues associated with conventional jaggery making.

2. VAPOUR RECOMPRESSION SYSTEM BASED JAGGERY MAKING

In this section, the analysis of VRS based jaggery-making process is discussed.

2.1 Vapor Recompression System

Vapour Recompression System, VRS, is used in the jaggery-making process to overcome the inefficiencies involved in the conventional jaggery-making process. The basic principle involves the compression of steam produced while heating raw juice and using it to heat the juice (Rane and Uphade, 2016). The system consists of a Latent Heat Exchanger (LHE) and compressor. LHE consists of a circular tube that is kept inside an outer rectangular tube. Raw juice is stored in the inner circular juice tube. This raw juice on heating produces steam which is passed to a steam compressor. After undergoing compression, this steam goes to the outer rectangular tube through which it heats the juice and the concentration process goes on. In this way, VRS enables the recycling of heat by compressing the vapour generated from the juice concentration process.

2.2 Necessity of Near Isothermal Steam Compressor

Juice concentration increases as the water evaporate from raw juice. The water removal rate is higher during the initial phase of water removal. This is due to low boiling point elevation and high heat transfer coefficient, 1,560 W/(m^2.K). Boiling point elevation increases from 0.56ºC at 20ºBrix to 18ºC at 90ºBrix. After the concentration process, temperature lift is increased because of the cumulative effect of boiling point elevation and the higher temperature approach required for heat exchange. This occurs due to a low heat transfer coefficient of 45 W/(m^2.K) at jaggery conditions. Suction pressure reduces much below that of raw juice condition. Hence, the compressor power required during the final stage of jaggery making is higher than during the initial phases with raw juice. Small capacity lubrication-free steam compressors are not available in the market (Hanlon, 2001). Judicious design of small capacity near isothermal steam compressor can save power. The pressure ratio across the compressor is low, 1.05 to 2.8. A novel isothermal compressor improves the overall efficiency of the system and can be used to serve the jaggery-making application at relatively lower power requirements.

2.3 Near Isothermal Steam Compressor

Near Isothermal Steam Compressor is a device where compression is achieved by elongation and compression of a flexible element like a spring passing over rotating pulleys. Several pistons spanning its entire length are placed equidistantly on the spring. These pistons pass through a tube that connects the high-pressure and low-pressure sides. The piston and tube arrangement resembles a piston-cylinder-like mechanism. When the spring elongates, a space is created between the pistons. The working fluid is accommodated in this space and is carried through the tube to the high-pressure side. After delivering the working fluid to the high-pressure side, the spring contracts, thus, eliminating the space created between the pistons. Owing to this, there is almost no working fluid present in the return cycle. There are no valves required for the inflow and outflow of the working fluid, thus, enabling compression of two-phase fluid in the compressor. The multi-stage system is illustrated in Figure 2 and Figure 3. As the process followed by the compressor is nearly isothermal, the work required for achieving the required compression is significantly lower as compared to its conventional small-capacity compressors. This helps in reducing the operating costs of the device. The device is a modular, scalable, energy-efficient and durable alternative to currently available alternatives.

This system can be beneficially coupled with the LHE of EEJM for jaggery-making applications. Several such systems can be coupled together to serve high-capacity application requirements. An easy-to-use portable jaggery-making unit can be integrated with the help of this compressor which has the potential to eliminate the inefficiencies involved in traditional jaggery making processes while eliminating the drudgery and heat stress experienced by the workers.

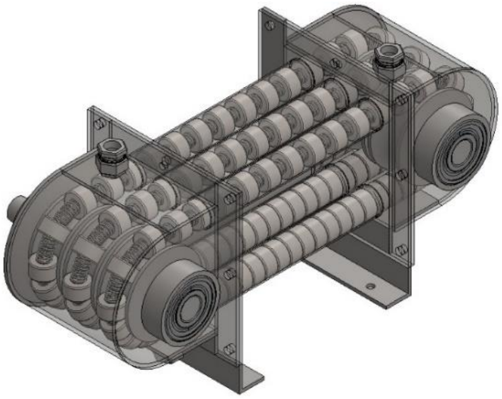

Figure 2: Isometric View of Multi-Stage Steam Compressor

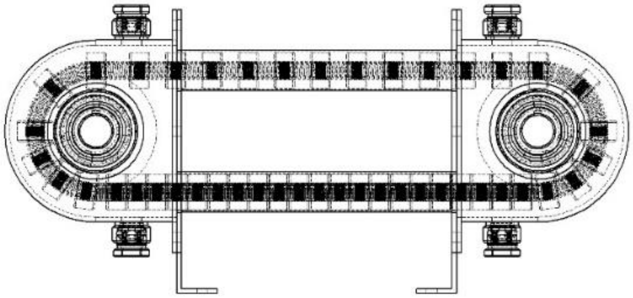

Figure 3: Front View of Multi-Stage Steam Compressor

2.4 Analysis of Vapor Recompression System-based Jaggery Making

In the proposed VRS, raw sugarcane juice can be concentrated at a lower boiling temperature of about 100°C as compared to the conventional open pan boiling process where temperatures can go up to 118°C with occasional hot spots. The concentration of juice at lower temperatures can reduce inversion and eliminate caramelisation while conserving the entire bagasse. In this section, a single-stage Vapour Recompression System is analysed for the concentration of sugarcane juice from 20°Brix to 90°Brix. For the stage-wise capacity calculations, a compressor of 15 lpm displacement rate is being considered to demonstrate a table-top jaggery-making unit. It is expected to be developed for 100 kg/d cane crushing which will produce 1 kg/h jaggery.

Assuming 12 h/day operation, h_{opd}, to be 12 h and mass of raw material, m_{rm}, to be 100 kg/d

Generally, wet bagasse, m_{wb} is 30 to 40% of total cane crushed which works out to 35 kg/d.

$$m_{wb} = 35\%\ m_{rm} \tag{1}$$

$$m_{rj} = m_{rm} - m_{wb} \tag{2}$$

Using Equation (2), the Mass of raw juice, m_{rj} works out to 65 kg/d. The total quantity of water evaporated is calculated using mass balance and concentration change from raw juice to jaggery. Taking the initial concentration of raw juice, $x_{stg.i}$, to be 20°Brix and the final concentration of jaggery, $x_{stg.f}$, to be 90°Brix.

Using concentration balance for sucrose,

$$m_{rj} \,.\, x_{stg.i} = m_{jg} \,.\, x_{stg.f} \tag{3}$$

Rearranging the terms,

$$m_{jg} = m_{rj} \,.\left(\frac{x_{stg.i}}{x_{stg.f}}\right) \tag{4}$$

Mass balance for the juice concentration process is given by,

$$m_{rj} - m_{jg} = m_{w.evp.tot} \tag{5}$$

Substituting Equation (4) in (5),

$$m_{w.evp.tot} = m_{rj} \,.\left(1 - \frac{x_{stg.i}}{x_{stg.f}}\right) \tag{6}$$

On Substituting $x_{stg.i} = 20$°Brix, $x_{stg.f} = 90$°Brix and $m_{rj} = 65$ kg/d, total water evaporated, $m_{w.evp.tot}$, is 50.5 kg/d

This is the total quantity of water to be evaporated for concentrating the raw juice into jaggery. The following calculations are performed by considering the evaporation of water in equal quantities in nine stages, $n_{p.stg} = 9$.

$$m_{w.evp.stg.n} = \frac{m_{w.evp.tot}}{n_{p.stg}} \tag{7}$$

Using Equation (7), the Mass of water to be evaporated per stage, $m_{w.evp.stg.n}$, works out to be 5.61 kg/d

Concentration at the outlet of each step, $x_{stg.f}$, by evaporation of water, is determined by using Equation (8),

$$x_{stg.f} = \frac{x_{stg.i}}{1 - \frac{m_{w.evp.stg.n}}{m_{rj.n}}} \tag{8}$$

For the first stage, $x_{stg.i} = 20$°Brix, $m_{w.evp.stg.n} = 5.61$ kg/d and $m_{rj.n} = 65$ kg/d, $x_{stg.f} = 21.9$°Brix

Boiling Point Elevation, BPE, is calculated using the following equation (Hugot 1986),

$$dt_{bpe.stg.1} = \frac{2 \,.\, x_{stg.f}}{100 - x_{stg.f}} \tag{9}$$

Stage 1 BPE, $dt_{bpe.stg.1}$, works out to be 0.56°C

As discussed earlier, Condenser Temperature, t_{cnd}, is 100°C. Assuming temperature approach for heat transfer, $dt_{he.s.n.asm.1} = 0.7$°C. Temperature of juice at stage 1,

$$t_{j.stg.1} = t_{cnd} - dt_{he.s.n.asm.1} \tag{10}$$

On substituting in Equation (10), temperature of juice at stage 1, $t_{j.stg.1}$, works out to 99.3°C

Temperature of water vapour at stage 1, $t_{wv.stg.1}$, is equal to temperature of juice at stage 1, $t_{j.stg.1}$, which is 99.3°C

Saturation temperature of water at stage 1, $t_{sat.w.stg.1}$, is 98.7°C.

$$t_{sat.w.stg.1} = t_{wv.stg.1} - dt_{bpe.stg.1} \tag{11}$$

Evaporator pressure corresponding to the saturation temperature of the water, $p_1 = 0.976$ bar

Condensation pressure is atmospheric, p_2 1.013 bar and t_{sat} 100°C

Density of superheated vapour at p_1 0.976 bar and $t_{wv.stg.1}$ 99.5°C, $\rho_{wv.stg.1}$ works out to 0.576 kg/m^3

Volume flow rate of diaphragm compressor, $volf_{cmp}$ = 15 lpm = 0.25 L/s

$$mf_{wv.cmp.1} = volf_{cmp} \cdot \rho_{wv.stg.1} \tag{12}$$

Mass flow rate of water vapour, $mf_{wv.cmp.1}$ = 0.144 g/s

Enthalpy of saturated vapour at p_1 0.976 bar and $t_{wv.stg.1}$ 98.94°C, $h_{l.sat.stg.1}$ = 414.6 kJ/kg, $h_{v.sat.stg.1}$ = 2673.9 kJ/kg

Enthalpy of superheated vapour at p_1 0.976 bar and $t_{wv.stg.1}$ 99.5°C, $h_{l.sup.stg.1}$ = 2675.1 kJ/kg

Evaporator heat duty, $Q_{evp.1}$, calculated using Equation (13) works out to be 325.3 W

$$Q_{evp.1} = mf_{wv.cmp.1} \cdot h_{lat.evp.1} \tag{13}$$

$$Q_{evp.1} = mf_{wv.cmp.1} \cdot (h_{v.sat.stg.1} - h_{l.sat.stg.1})$$

Overall heat transfer coefficient corresponding to stage 1, $U_{o.he.stg.1}$ is 1,560 W/m^{2}K
Area for heat exchange is,

$$A_{he} = \pi \cdot d_t \cdot l_t \tag{14}$$

For the latent heat exchanger, d_t 76.2 mm and l_t 1,216 mm, so the available heat transfer area, A_{he} is 0.291 m^2
Temperature approach for heat exchange, $dt_{he.s.n.cal.1}$ works out to be 0.71°C

$$dt_{he.s.n.cal.1} = \frac{Q_{evp.1}}{U_{o.he.stg.1} \cdot A_{he}} \tag{15}$$

Table 1: Stage-wise steam flow rate for jaggery-making process

Sr	**$x_{stg.i}$**	**m_{rj}**	**$m_{w.evp.stg.n}$**	**$x_{stg.f}$**	**$bpe_{stg.f}$**	**$\Delta t_{he.s.n.asm}$**	**t_{sat}**	**Δh**	**Time**	**$\dot{m}_s$**	**U**	**$\Delta t_{he.s.n.cal}$**
#	°Brix	kg	kg	°Brix	°C	°C	°C	kJ/kg	min	**g/s**	W/m^{2}K	°C
1	**20.0**	1.300	0.11	21.9	**0.56**	0.70	**98.7**	2,262.4	13	**0.143**	1,560	**0.71**
2	**21.9**	1.188	0.11	24.2	**0.64**	0.80	**99.4**	2,259.5	13	**0.146**	1,400	**0.81**
3	**24.2**	1.075	0.11	27.0	**0.74**	0.74	**99.3**	2,260.0	13	**0.146**	1,300	**0.87**
4	**27.0**	0.963	0.11	30.6	**0.88**	0.88	**99.1**	2,260.6	13	**0.145**	1,200	**0.94**
5	**30.6**	0.851	0.11	35.2	**1.09**	1.09	**98.9**	2,261.6	13	**0.144**	1,050	**1.07**
6	**35.2**	0.738	0.11	41.5	**1.42**	1.42	**98.6**	2,263.2	13	**0.143**	1,000	**1.11**
7.1	**41.5**	0.626	0.06	45.6	**1.68**	1.68	**98.3**	2,264.4	7	**0.141**	950	**1.16**
7.2	**45.6**	0.570	0.06	50.6	**2.05**	2.05	**97.9**	2,266.1	7	**0.140**	900	**1.21**
8.1	**50.6**	0.514	0.06	56.8	**2.63**	2.63	**97.4**	2,268.8	7	**0.137**	800	**1.33**
8.2	**56.8**	0.457	0.06	64.8	**3.68**	3.68	**96.3**	2,273.7	7	**0.132**	550	**1.88**
9.1	**64.8**	0.401	0.03	69.7	**4.60**	4.60	**95.4**	2,278.0	4	**0.128**	400	**2.50**
9.2	**69.7**	0.373	0.03	75.3	**6.11**	6.11	**93.9**	2,285.0	4	**0.121**	120	**7.95**
9.3	**75.3**	0.345	0.03	82.0	**9.13**	9.13	**90.9**	2,298.8	4	**0.109**	50	**17.26**
9.4	**82.0**	0.317	0.03	90.0	**18.0**	18.0	**82.0**	2,338.9	6	**0.079**	45	**14.13**

The above calculations are repeated for other stages of juice concentration and respective values have been illustrated in Table 1. It can be observed that as juice concentration progresses, boiling point elevation increases from 0.56 ^{o}C in raw juice condition to 18^{o}C in jaggery condition. The overall heat transfer coefficient also reduces significantly.

3. SPRING DESIGN FOR ENERGY-EFFICIENT COMPRESSOR

In this section, the design calculations for spring have been discussed. The stretching of spring based on pressure differential has been calculated for different process conditions.

3.1 Design Objective

Spring design should possess the required strength to withstand the pressure difference between high and low-pressure chambers.

3.2 Design Constraints and Factors of Safety Considerations

In the energy-efficient compressor, the spring has to engage with the internal threads of the piston assembly. For the configuration in which the spring is assembled in the piston hole, the outer dimension, $d_{s.c.o}$, of the spring restricts the hole diameter of the piston. This configuration may be used for low-pressure difference and higher flow rate applications.

The factor of safety in the design of springs is usually 1.5 or less. The low factor of safety value is because there are usually low residual stresses present in the spring wire owing to its thin cross-section which leads to uniform heat treatment and cold-working. This reduces the risk of sudden failure while in the application (Bhandari, 2010).
As recommended by Indian Standard 4454-2001, FOS of 2 is selected.

3.3 Design Calculations

As per Indian Standard 4454–2001, the permissible shear stress is given by,

$$\tau_{per} = 0.5\ S_{ut} \tag{16}$$

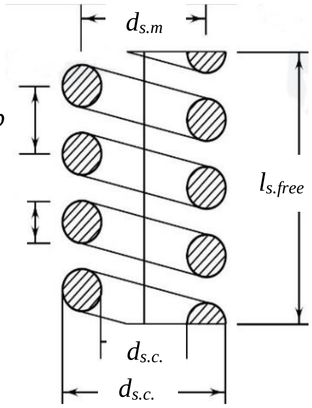

Figure 4: Dimensions of closed coiled helical spring (CCHS)

The following calculations have been performed by taking, $d_{s.w}$ = 1.2 mm
For a cold- drawn steel wire of grade SS 304 with $d_{s.w}$ = 1.2 mm,
The ultimate strength is, S_{ut} = 1,500 N/mm^2
Hence, Permissible Shear Stress, τ_{per} = 0.5 (1,500 N/mm^2) = 750 N/mm^2
The outer diameter of the spring is governed by the bore of piston.
Hence, $d_{s.c.o}$ = 12.5 mm and $d_{s.c.i}$ = 10.1 mm

$$d_{s.c.i} = d_{s.c.o} - 2\ d_{s.w} \tag{17}$$

Spring Index, C = 10.6

$$C = \frac{d_{s.m}}{d_{s.w}} \tag{18}$$

Mean Coil diameter, $d_{s.m}$ = 11.3 mm

$$d_{s.m} = \frac{d_{s.c.o} + d_{s.c.i}}{2} \tag{19}$$

Wahl Stress Factor, K = 1.14

$$K = \frac{4\,C - 1}{4\,C - 4} + \frac{0.615}{C} \tag{20}$$

3.4 Calculation of Induced Shear Stress ($\tau_{induced}$)

The maximum pressure, p_{max}, that the system reaches is slightly above atmospheric pressure 1.05 bar while the minimum pressure on the evaporator side would range between 0.375 bar and 0.5 bar depending upon heat exchanger effectiveness. To account for variation in heat transfer coefficient and associated temperature and pressure difference as well as an additional factor of safety, the calculations are performed for the minimum pressure, p_{min}, of 0.33 bar.

The standard available tube size for piston-cylinder arrangement is 25.4 mm in diameter with 1.22 mm wall thickness. Based on this, the following piston diameter is selected for the first set of calculations.
The diameter of the piston, d_p, is 22.96 mm.
Piston Area, A_p, calculated using Equation (21) works out to be 4.15 cm^2

$$A_p = \frac{\pi\, d_p^2}{4} \tag{21}$$

From above discussion, p_{max} = 1.05 bar = 1,05,000 N/m^2 and p_{min} = 0.33 bar = 33,000 N/m^2

$$F_{p.hp} = P_{max}\, A_p \tag{22}$$

Force on the piston on the high-pressure side, $F_{p.hp}$, is calculated using Equation (22) and it works out to 43.6 N

$$F_{p.lp} = p_{min}\, A_p \tag{23}$$

Force on piston on low pressure side is calculated using Equation (23) and it works out to $F_{p.lp}$ = 13.7 N = 1.4 kgf
Net Applied Load, $F_{p.net}$, is calculated using Equation (24) and it works out to 29.9 N

$$F_{p.net} = F_{p.hp} - F_{p.lp} \tag{24}$$

Induced Shear Stress, $\tau_{induced}$ = 567.8 N/mm^2

$$\tau_{induced} = \frac{8\,K\,F_{p.net}\,d_{s.m}}{\pi\, d_{s.w}^3} \tag{25}$$

As $\tau_{induced}$ = 567.9 N/mm^2 is less than the permissible shear stress, τ_{per} = 750 N/mm^2, hence the first design objective is achieved.

3.5 Calculation of Spring Deflection, δ

Spring Deflection, δ, is given by,

$$\delta = \frac{8\,F_{p.net}\,d_{s.m}^3\,N_{s.t}}{G\,d_{s.w}^4} \tag{26}$$

For the cold drawn steel wire of grade SS304, modulus of rigidity, G = 81,370 N/mm^2.

The other parameters needed to calculate δ are,

The mean wire diameter, $d_{s.m}$ is 11.3 mm,

The net force acting on the piston, $F_{p.net}$ is 29.9 N

Calculation of Number of Active Turns, $n_{s.t}$, is as follows, The length of the cylindrical tube through which the spring has to pass, l_{bep}, is 124.6 mm. The length of the unsupported section of spring between the centreline of the shaft and endplate on the left side, $l_{scl.epf.l}$, is 81.2 mm. Similarly, the distance between the shaft centreline and endplate on the right side, $l_{scl.epf.r}$, is 81.2 mm.

The total length of spring, $l_{tot.str}$, is calculated using Equation (27) and it works out to be 287 mm.

$$l_{tot.str} = l_{bep} + l_{scl.epf.l} + l_{scl.epf.r} \tag{27}$$

The length of each piston, l_p is 12.7 mm. So, if pistons are placed over the spring without any gap between them, then, the number of the piston on the stretched side $n_{p.s}$, is 22.5.

$$n_{p.s} = l_{tot.str} / l_p \tag{28}$$

The number of pistons on the spring is taken as 22. Since a closed pitch spring is used in this application so the pitch of spring is given by, $p_{s.c} = d_{s.w}$. The number of turns per piston, n_c, is 10.6.

$$n_c = \frac{l_p}{p_{s.c}} \tag{29}$$

Assuming that out of these 10 turns, the movement of 4 turns are restricted as they are locked, with the threads on the piston meaning it is not free to stretch. The other 6 turns are free to stretch. Hence, the number of active turns per piston, $n_{act.tpp}$, is 6. The total number of active turns, $n_{s.t}$, is 132.

$$n_{s.t} = n_{p.s} .n_{act.tpp} \tag{30}$$

Substituting values in Equation (26), total deflection, δ, works out to be 270.1 mm. This value is the total deflection across all the pistons in one cylinder. Deflection between two pistons, δ_p, works out to be 12.3 mm.

As the juice concentration, measured in °Brix, increase, the vapour pressure of the steam generated reduces. This increases the pressure difference across the two chambers. The calculations for the same have been performed in the above manner in Table 2 for various juice concentrations.

It can be observed that as raw juice gets concentrated, the vapour generated per unit change in concentration reduces, and the vapour pressure reduces. This results in higher pressure differences while operating at higher concentrations, resulting in higher deflection of spring.

Table 2: Spring deflection calculations

Stages of Juice Concentration		**p_v**	**$F_{p.hp}$**	**$F_{p.lp}$**	**$F_{p.net}$**	**Deflection, δ**	**δ / n**
°Brix		bar	N	N	N	mm	mm
20.0	22.2	0.95	39.5	39.5	0.00	0.0	**0.000**
22.2	24.8	0.94	39.5	39.1	0.42	3.6	**0.148**
24.8	28.2	0.93	39.5	38.6	0.83	7.1	**0.296**
28.2	32.7	0.92	39.5	38.2	1.25	10.7	**0.444**
32.7	38.9	0.91	39.5	37.8	1.66	14.2	**0.592**
38.9	43.0	0.91	39.5	37.6	1.87	16.0	**0.666**
43.0	48.0	0.90	39.5	37.4	2.08	17.8	**0.740**
48.0	54.3	0.87	39.5	36.1	3.32	28.4	**1.184**
54.3	62.6	0.83	39.5	34.5	4.99	42.6	**1.776**
62.6	67.8	0.80	39.5	33.2	6.23	53.3	**2.221**
67.8	73.8	0.75	39.5	31.2	8.31	71.1	**2.961**
73.8	81.1	0.62	39.5	25.8	13.71	117.2	**4.885**
81.1	90.0	0.35	39.5	14.5	24.93	213.2	**8.882**

3.5 Calculation of Compressor Displacement Rate

The near isothermal compressor can be run by coupling it with a motor running at a speed of, n_{mtr}, 720 rpm. The pulley diameter, $d_{m.p}$, selected for the system is 76.2 mm. The piston speed is calculated using Equation (31) which works out to be 2.87 m/s.

$$v_p = \frac{\pi\, d_{m.p}\, n_{mtr}}{60} \tag{31}$$

Piston Area, A_p, calculated using Equation (21) works out to be 4.15 cm^2. Using Equation (32), the flow rate from the system can be calculated.

$$volf_{cmp} = \frac{A_p\, v_p\, n_{s.t}}{n_{tot}} \tag{32}$$

The total number of turns on the stretched side, n_{tot}, is 220 and the number of active turns of these is, $n_{s.t}$, 132. On substituting the values in Equation (32), the volume flow rate, $volf_{cmp}$, works out to be 714.6 cm^3/s.

4. CHALLENGES ALONG WITH POSSIBLE SOLUTIONS

The conventional jaggery-making process involves boiling of juice in open pans and has low thermal efficiency in the range of 15% to 50% depending on the number of evaporator pans. It exposes labourers to severe heat stress, steam and fumes from furnaces. The quality of jaggery produced is low owing to caramelisation and inversion of sugar. Owing to these factors, the profits reduce while the fuel and labour costs increase.

In EEJM, the practice of boiling juice in open pans is eliminated due to the use of the Vapour Recompression System, VRS. Hot spots are eliminated as the surface temperature of the steam condenser tube is limited to 100°C, with the compressor discharging at atmospheric pressure. Exposure of the juice to oxygen in the air is reduced which improves the quality of the jaggery.

The challenges identified along with possible solutions to improve the techno-economic viability of VRS-based EEJM are summarized hereafter.

a. The development of low-cost, small-capacity, positive displacement type of two-phase compressors is essential to the widespread use of VRS-based jaggery-making systems.
b. A multi-module energy-efficient compressor can be developed to process up to 1 tpd cane crushing and 5 kg jaggery per h for 20 h/day operations.

5. CONCLUSION AND RECOMMENDATIONS

The conventional jaggery-making process involves open pan boiling which is inefficient and drudgery-ridden. An energy-efficient process based on Vapour Recompression System, VRS, is proposed for a tabletop jaggery maker using a novel Near Isothermal Steam Compressor. The design and analysis of sub-components and assemblies of the compressor of the Energy Efficient Jaggery Maker, EEJM, is presented. As the juice concentration progresses, boiling point elevation increases from 0.56ºC at 20ºBrix to 18ºC at 90ºBrix. This leads to a reduction in the heat transfer coefficient. This increases the heat transfer approach. Due to this, there is variation in spring deflection which further affects the volume flow rate of the system. Based on the current work, calculations for the spring deflection during different stages of juice concentration have been performed. The sizing of subcomponents of the compressor capable of handling the steam-water mixture is presented. The compressor is currently being integrated and will be coupled with a benchtop jaggery-making unit. Development of the EEJM will help the sugarcane farmers by way of improved earnings and reduced drudgery while enabling the production of better quality jaggery.

NOMENCLATURE

Abbreviations

A	area	(m^2)
C	spring index	(-)
h	enthalpy	(kJ/kg)
l	length	(mm)

n	number of turns	(-)
p	pitch	(mm)
Q	heat duty	(kW)
t	temperature	(ºC)
x	concentration	(ºBrix)
U	overall heat transfer coefficient	(W/(m^2.K))
volf	volumetric flow	(m^3/s)
Subscripts		
act	actual	
app	approach	
bep	between end plates	
bpe	boiling point elevation	
cmp	compressor	
cal	calculated	
evp	evaporator	
f	final	
he	heat exchange	
i	initial	
jg	jaggery	
l	liquid	
o	overall	
p	piston	
per	permissible	
rm	raw material	
rj	raw juice	
stg	Stage	
scl	shaft centerline	
s	steam	
tot	total	
t	tube	
sat	saturated	
sup	superheated	
ut	ultimate	
w	water	
wb	wet bagasse	
Greek Letters		
δ	deflection	(mm)
η	efficiency	(%)
ρ	density	(kg/m^3)

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ACKNOWLEDGEMENT

This work was funded by Tata Centre for Technology and Design, IIT Bombay, Mumbai, India through Grant # TCTD/DON/2015/125835. Support of Tata Centre for Technology and Design, IIT Bombay is gratefully acknowledged.