

CRYOGENIC

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Abstract:-- The term cryogenics is used to describe methods of refrigeration at very low temperatures (typically below 125 K), and distinguish them from ordinary refrigeration cycles. Many of these methods relate to the liquefaction of gases known as permanent, like air, natural gas, hydrogen or helium. Cryogenic liquid is used to directly or indirectly cool solid or liquid contaminants adhering to apparatus surfaces to effect a change in the physical characteristics of the contaminants and thereby render them more susceptible to removal operations. The challenges facing machining industries today are high metal removal rate and better product quality. Grinding is vital to many Manufacturing processes as it generates finer surfaces and closer dimensional tolerances. Cryogenics or deep freezing have been around for quite some time. There is documented research from as far back as the 1930's where German companies used it on components of jumbo aircraft engines. The austenite is unstable at this temperature and the whole structure become martensitic. This is the region to use cryogenic treatment. Processing is not a substitute for heat treating if the product is properly treated or if the product is over heated during remanufacturing or if it is over stressed during use. Cryogenic processing will not in itself harden metal like quenching and tempering, it is an additional treatment to heat-treating.

Keyword: Cryogenic, refrigeration cycles, high metal, cryogenic heat Treatment..

I. INTRODUCTION

Cryogenics is the science that addresses the production and effects of very low temperatures. The word originates from the Greek words 'kryos' meaning "frost" and 'genic' meaning "to produce." "Cryogenic hardening is a cryogenic treatment process where the material is cooled to very low temperatures. By using liquid nitrogen, the temperature can go as low as -190°C . It can have a profound effect on the mechanical properties of certain materials, such as steels or tungsten carbide [1]. Cryogenic processing had its US origins in the 1940s Cold treatments or sub-zero treatments are done to make sure there is no retained austenite during quenching [2]. Cryogenics is a relatively new process and to eliminate retained austenite, the temperature has to be lowered, but one that using correct procedures can bring substantial economic benefits [3]. In Cryogenic treatment the material is to be deep freeze temperatures of as low as -185°C (-301). The benefits of this process includes; reduction of abrasive and adhesive wear, improved machining properties resulting from the permanent change of the structure of the metal, reduction of the frequency and cost of tool remanufacturing and reduction of likelihood of catastrophic tool failure due to stress fracture[4]. Cryogenic processing makes changes to the structure of the materials being treated and dependent on the composition of the material, it performs three things; viz. retained

austenite turned to martensitic, carbide structures are refined and stress is relieved.

There are four cryogenic families:

1. Isenthalpic expansion Joule-Thomson processes
2. Isentropic expansion reverse Brayton cycles
3. Mixed processes involving isenthalpic and isentropic expansion (Claude cycle)
4. Conventional or integrated cascades.

1.1 Joule-Thomson Isenthalpic Expansion Process

We illustrate this process by some examples of cycles for liquefying natural gas and form Liquefied Natural Gas (LNG), considered here as pure methane. Methane liquefaction basic cycle

a) To liquefy natural gas methane taken at 1 bar and 280 K is compressed to 100 bar and then cooled to 210 K (it is assumed in this example that a refrigeration cycle is available for that).

b) Isentropic compression is assumed, but the very high compression ratio requires the use of several compressors (3 in this example) with intermediate cooling at 280 K. Intermediate pressures are equal to 5 and 25 bar.

c) The gas cooled at 210 K is isenthalpic ally expanded from 100 bar to 1 bar, and gas and liquid phases separated. As shown in the diagram in Figure below, the methane enters in the upper and liquid and gaseous fractions exit in the bottom right.

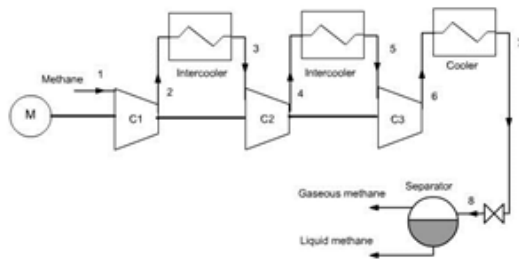


Figure 1.1: Joule-Thomson Isenthalpic Expansion Process

1.2 THE LINDE CYCLE

(Figure 1.2) improves the Previous on two points:

- gaseous methane is recycled after isenthalpic expansion;
- We introduce a heat exchanger between the gaseous methane and methane out of the cooler in order to cool the compressed gas not at 210 K but at 191 K.

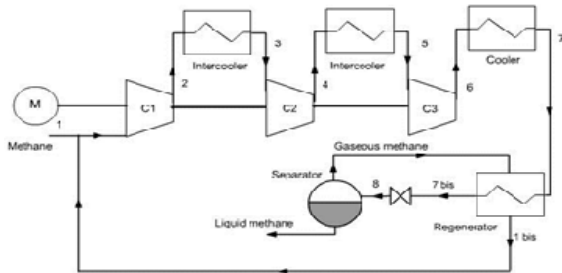


Figure 1.2: Linde cycle

1.3 Reverse Brayton Cycle: The reverse Brayton cycle has been presented in a thematic page, which we recommend you to refer to for details. This cycle can be used for cryogenic applications [2]. In this cycle, helium is compressed to 20 bar, then cooled to 30°C before being divided into two streams which are expanded in parallel, the main stream following a conventional reverse Brayton cycle, while the secondary contributes to cooling the total flow.

Mixed Processes: Claude Cycle: The Linde cycle uses isenthalpic expansion which has two drawbacks: firstly the expansion work is lost, and secondly cooling cannot be achieved if the fluid thermodynamic state is such that the Joule Thomson expansion leads to a temperature lowering. Claude has proposed a cycle that involves a turbine and an expansion valve and has the peculiarity that the plant operates with a single fluid compressed at a single pressure level, as shown in Figure below. The Claude cycle has been used in many air liquefying facilities [1].

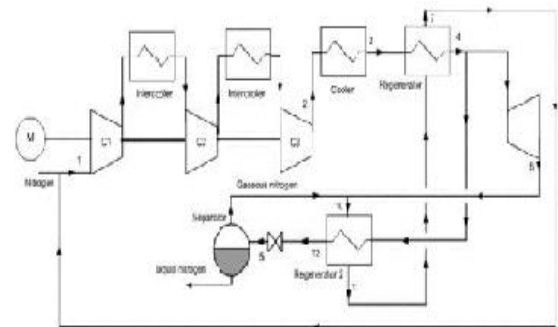


Figure 1.3: Reverse Brayton Cycle

The advantage of this cycle is that the compression ratio can be significantly lower than in the case of the Linde cycle. One difficulty is that the expansion machine cannot operate with good efficiency if the fluid remains in the vapour zone or keeps a high quality [2]. The originality of the Claude cycle is to combine isentropic expansion in the turbine, and isenthalpic expansion only in expansion leading to the gas liquefaction [3].

The beginning of the cycle is the same as that of Linde: compression of gas to liquefy, then cooling to about room temperature (1–3). The gas then passes through a regenerator which allows it to cool at about -105°C (3–4). The flow is then divided, about 15% being expanded in a turbine (4–8). The main flow passes through a second regenerator of which it is released at very low temperature (4–12). It undergoes isenthalpic expansion (12–5) and the liquid phase is extracted. The vapor is mixed with the flow exiting the turbine, and serves as a coolant in the second regenerator (10–11), then in the first (11–7) before being recycled by mixing with the gas entering the cycle.

1.4 Cascade System

It is also possible to use cascading refrigeration cycles, the evaporator of one of them serving as a condenser to another and so on (Figure 1.5). The various cooling circuits are then independent from the hydraulic, but thermally coupled by their evaporative condensers [3]. An alternative, widely used nowadays in the liquefaction of natural gas, is to use a so-called incorporated cascade, using a single working fluid consisting of a mixture of methane, ethane, propane, butane and pentane.

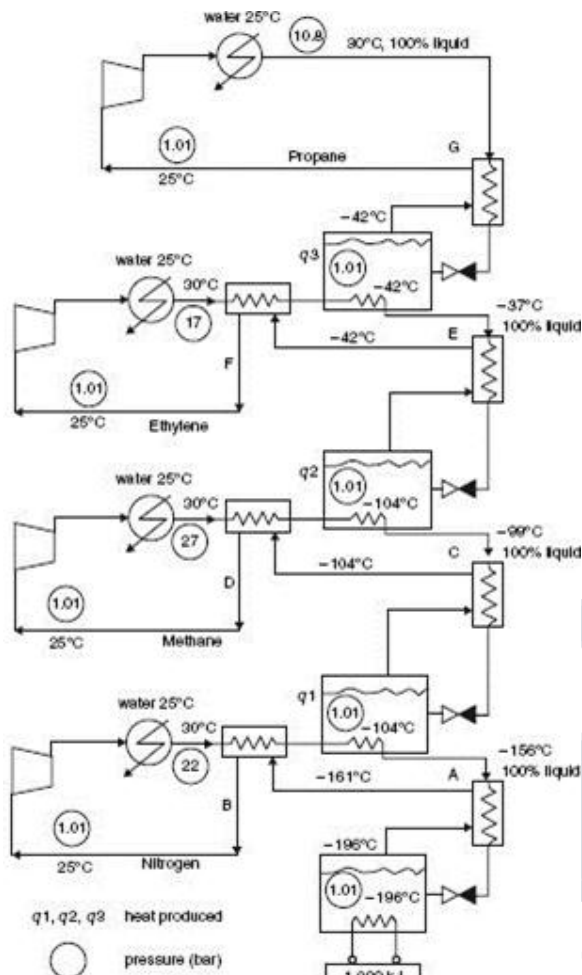


Figure 1.4: Cascade System

II. METHODS/ PROCEDURE

2.1 Work Required For Liquefaction In A Thermodynamically Ideal System [5]:

We illustrate this process by some examples of cycles for liquefying system Simple Linde-Hampson System for Liquefaction of Gases Other Than Neon, Hydrogen and Helium, Pre-Cooled Linde-Hampson System.

A thermodynamically ideal liquefier system is shown below, along with its T-s diagram. In the ideal system, all the gas compressed is liquefied.

- 1-2: isothermal compression to a required high pressure
- 2-f: isentropic expansion, such that all the compressed gas is liquefied after expansion.

Applying the I Law to the entire system, neglecting changes in P.E. and K.E., we get [5]:

$$-\frac{\dot{W}_i}{\dot{m}} = T_1(s_1 - s_f) - (h_1 - h_f) = -\frac{\dot{W}_i}{\dot{m}_f}$$

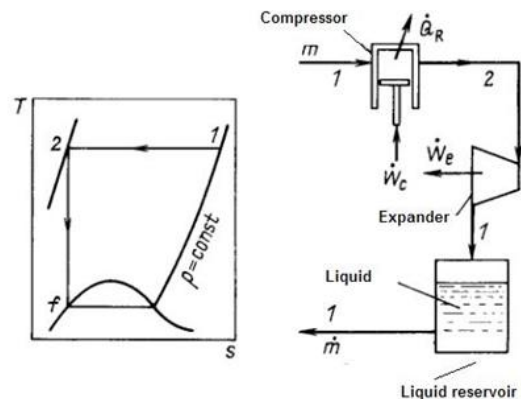


Figure 2.1: Thermodynamically ideal liquefaction system
Ideal work of liquefaction for a few gases, starting from 300 K, 101.3 kPa are given below [5]:

Gas	Normal Boiling Point		Ideal Work of Liquefaction, $-\dot{W}_i/\dot{m}_f$	
	K	°R	kJ/kg	Btu/lb _m
Helium-3	3.19	5.74	8 178	3 516
Helium-4	4.21	7.58	6 819	2 931
Hydrogen, H ₂	20.27	36.5	12 019	5 167
Neon, Ne	27.09	48.8	1 335	574
Nitrogen, N ₂	77.36	139.2	768.1	330.2
Air	78.8	142	738.9	317.7
Carbon monoxide, CO	81.6	146.9	768.6	330.4
Argon, A	87.28	157.1	478.6	205.7
Oxygen, O ₂	90.18	162.3	635.6	273.3
Methane, CH ₄	111.7	201.1	1 091	469
Ethane, C ₂ H ₆	184.5	332.1	353.1	151.8
Propane, C ₃ H ₈	231.1	416.0	140.4	60.4
Ammonia, NH ₃	239.8	431.6	359.1	154.4

Figure 2.2: ideal work for liquefaction system from 300K, 101.32kpa

Above mentioned 'Ideal liquefaction system' is not practically possible since:

- i) Because of the nature of T-s diagram, the pressure required would be extremely high
- ii) The isentropic expansion in an expansion engine to the liquid point is impractical in the presence of two-phase fluid.

III. SIMPLE LINDE-HAMPSON SYSTEM FOR LIQUEFACTION OF GASES OTHER THAN NEON, HYDROGEN AND HELIUM [5, 10]:

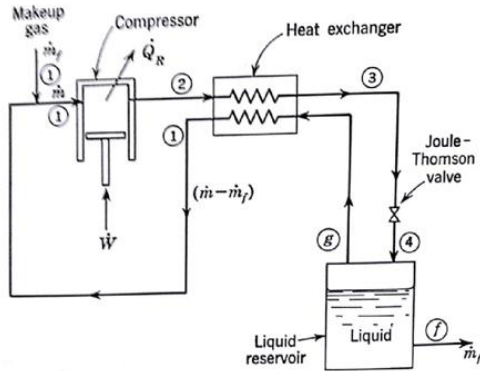
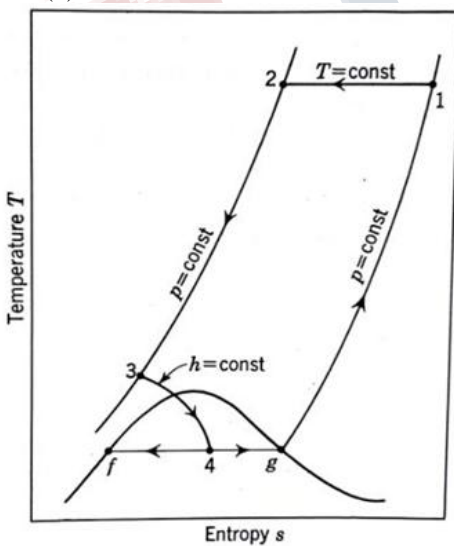


Figure 2.3: Simple Linde-Hampson System For Liquefaction Of Gases Other Than Neon, Hydrogen And Helium

In the below graph 2.1

- 1-2: Isothermal compression in the compressor
- 2-3: Cooling to a low temp in the heat exchanger, by heat exchange with the returning cold stream
- 3-4: J-T expansion in the expansion valve, resulting in liquefaction (4)



Graph 2.1: entropy vs temperature for Simple Linde-Hampson System

g-1: returning cold gas stream in the heat exchanger
Applying the I Law to the whole system (except the compressor):

$$0 = (\dot{m} - \dot{m}_f) h_1 + \dot{m}_f h_f - \dot{m} h_2$$

Or, the liquid yield is given by:

$$\frac{\dot{m}_f}{\dot{m}} = y = \frac{h_1 - h_2}{h_1 - h_f}$$

Note that h_1 and h_f are determined by the ambient conditions; and the variable in our control is h_2 . It can be shown that for maximum yield, the point 2 must lie on the Inversion curve. For air, with the ambient at 294 K, this pressure is about 400 atm, but actual systems use about 200 atm. Remember that to produce cooling, temp before J-T expansion should be below the Max inversion temp. Compressor work requirement is obtained by applying the I Law to the compressor:

$$\dot{W}_c - \dot{Q}_r + \dot{m}(h_1 - h_2) = 0$$

And, heat transferred in compressor for isothermal compression:

$$\dot{Q}_r = \dot{m} T_1 (s_1 - s_2)$$

And, the work required:

$$\frac{\dot{W}_c}{\dot{m}} = T_1 (s_1 - s_2) - (h_1 - h_2)$$

Then,

$$\frac{\dot{W}_c}{\dot{m}_f} = \frac{\dot{W}_c}{\dot{m} y} = [T_1 (s_1 - s_2) - (h_1 - h_2)] \left(\frac{h_1 - h_f}{h_1 - h_2} \right)$$

2.3 Pre-Cooled Linde-Hampson System [5,10]:

Recall that for the simple Linde-Hampson system, the liquid yield is given by: Since h_1, h_f are fixed by ambient conditions, we can increase the liquid yield by decreasing h_2 , i.e. by reducing the temp at point 2, i.e. at the inlet to the heat exchanger [12]

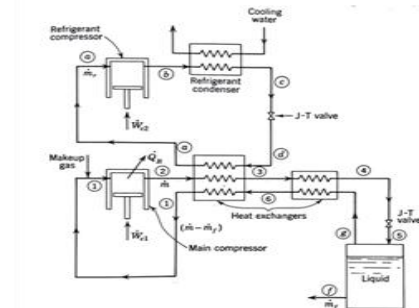


Figure 2.4: Pre-Cooled Linde-Hampson System

Here, we have:

- 1-2: Isothermal compression
- 2-3: Cooling in the first heat exchanger by the auxiliary refrigeration system
- 3-4: Cooling in the J-T heat exchanger
- 4-5: Expansion in the J-T valve
- g-1: return path of gas

III. OBSERVATION /RESULT (MATH/UNITS)

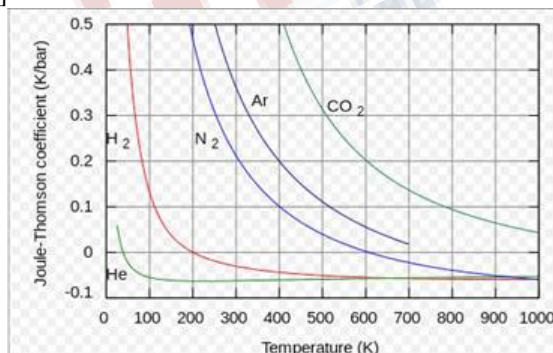
3.1 Thermodynamic Background: Joule-Thomson (J-T) Or Isenthalpic Expansion:

When a high pressure gas passes through a valve, capillary or restriction, its pressure drops and the temperature also drops, generally [6]. From the I Law of Thermodynamics, it can be shown that in this process the enthalpy remains constant. Joule-Thomson coefficient is defined as [15].

$$\mu_{JT} = \left(\frac{\partial T}{\partial P} \right)_H$$

Obviously,

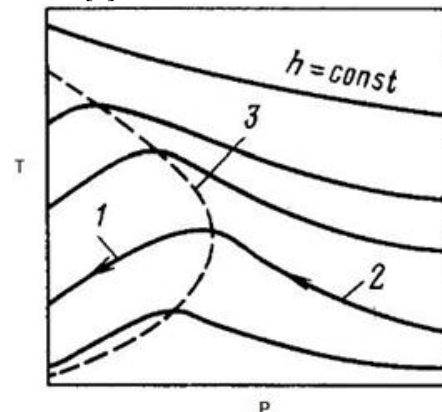
$\mu_{JT} > 0$ to produce a temp drop as the pressure drops, $\mu_{JT} < 0$ for a temp increase as the pressure drops, and if $\mu_{JT} = 0$, then there is no change in temp as the pressure drops through the J-T valve [8]. Hydrogen, helium, and neon have negative J-T coefficients at ambient temperature; therefore, these gases have to be pre-cooled to temperatures below their respective 'max. Inversion temperatures', if they have to produce cooling upon expansion in a J-T valve. Following graph illustrates this [13]



Graph 3.1: entropy vs temperature for Simple Linde-Hampson System

3.2 Inversion curve:

Pressure vs Temp curves at constant enthalpies for a gas look as follows [5]



Graph 3.2: Pressure vs Temp for inversion curve

Pressure vs Temp curves at constant enthalpies for a gas look as follows [1] Note from the above Table that max. inversion temps for Neon, Hydrogen and Helium are below the room temp (300 K); therefore, these three gases will have to be pre-cooled to a temperature below their respective max. inversion temperature [14]. Note from the above graph that constant enthalpy curves go through a maximum. Locus of these maximums is called '**Inversion line**' (3 in fig. above) and the point where this inversion line cuts the y-axis (i.e P = 0) is known as '**Max. inversion temp.**' Note that Inversion line divides the P-T graphs in to two regions, viz. [9].

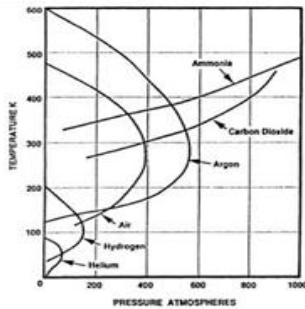
- i) Region of cooling upon expansion, i.e. J-T coeff. > 0 , is to the left of the Inversion curve (region 1 in fig. above),
 - ii) Region of heating upon expansion, i.e. J-T coeff. < 0 , is to the right of the Inversion curve (region 2 in fig. above).
- Following Table gives max. Inversion temperatures for a few gases [7].

Fluid	Maximum inversion temperature	
	K	°R
Oxygen	761	1370
Argon	722	1300
Nitrogen	622	1120
Air	603	1085
Neon	250	450
Hydrogen	202	364
Helium	40	72

Table No 3.1: Max Inversion of few gases

Note from the above Table that max. Inversion temps for Neon, Hydrogen and Helium are below the room

temp (300 K); therefore, these three gases will have to be pre-cooled to a temperature below their respective max. inversion temperatures to produce cooling upon a J-T expansion^[16]. Joule-Thomson Inversion curves for a few common gases are shown below: [4]



Graph 3.3: Pressure vs Temp for Joule-Thomson inversion

curve

For a 'Real gas' which is represented by the Van der Waal's equation^[15].

$$\left(p + \frac{a}{v^2}\right)(v - b) = RT,$$

where 'a' is a measure of intermolecular forces and 'b' is a measure of the finite size of the molecules^[10]. Here, a and b are calculated in terms of the critical temp (T_c) and critical pressure (P_c)

$$a = \frac{27}{64} \frac{R^2 \cdot T_c^2}{P_c}$$

$$b = \frac{1}{8} \frac{R \cdot T_c}{P_c}$$

We have, for J-T coeff. by definition [11]:

$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h$$

Note that J-T coeff for a Perfect gas is zero, i.e. a Perfect gas will undergo no temperature drop during a J-T expansion.

Units: p...N/m²

m³/kg.mol

T...K

R = Universal gas constant = 8314.4 Nm/kg.mol.K

a...Nm⁴/(kg.mol)²

b...m³/kg.mol

Values of Van der Waal's constants a and b, and pressure and temp at critical point for some gases are given below [12]: of a given gas

Substance	a (J. m ³ /kg.mole ²)	b (m ³ /kg.mole)	P _c (MPa)	T _c (K)
Air	135800	0.0364	3.77	133
Carbon Dioxide	364300	0.0427	7.39	304.2 K
Nitrogen (N ₂)	136100	0.0385	3.39	126.2
Hydrogen (H ₂)	24700	0.0265	1.3	33.2
Water (H ₂ O)	550700	0.0304	22.09	647.3
Ammonia (NH ₃)	423300	0.0373	11.28	406
Helium (He)	3410	0.0234	0.23	5.2
Freon (CCl ₂ F ₂)	1078000	0.0998	4.12	385

Table No 3.2: Values of Van der Waal's constants a and b, and pressure and temp at critical point for some gases are given below [12]: Some Tables give values of a and b in different Units. Then, following conversion factors can be used (remember: 1J = 1Nm)

It is important to remember proper units while using the Van der Waal's equation^[13].

$$\mu_{JT} = \frac{1}{c_p} \left[T \left(\frac{\partial v}{\partial T} \right)_p - v \right]$$

From Thermodynamics, we can show that: where v is the sp. volume.

Now, for a 'perfect gas', we have:

$$p \cdot v = R \cdot T,$$

and, we get, J-T coeff. for a Perfect gas as:

$$\mu_{JT} = \frac{1}{c_p} \left[T \left(\frac{v}{T} \right) - v \right] = 0.$$

For large values of sp. volume, above eqn can be approximated to

$$\mu_{JT} = \frac{1}{c_p} \left(\frac{2a}{RT} - b \right),$$

Inversion temp for a Van der Waal's gas is given by:

$$T_i = \frac{2a}{bR} \left(1 - \frac{b}{v} \right)^2$$

And, the max. Inversion temp is the temp on the inversion curve at p = 0, and is given by^[14].

$$T_{\max} = 2a/bR$$

IV.CONCLUSION

This brief paper has presented the basic ideas and principles of the most important aspects of cryogenics, i.e. Isenthalpic expansion Joule-Thomson processes, isentropic expansion reverse Brayton cycles, Mixed processes involving isenthalpic and isentropic expansion (Claude

cycle), Conventional or integrated cascades. It has also provided the reader with typical numerical values of the relevant parameters, related to Claude & Joule Thomson processes.

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