

---

**Appendix A1: The British Patent No. 2064,  
of Dr. Charles Williams Siemens, 1857:  
“Refrigeration Apparatus”**



A.D. 1857 . . . . . N° 2064.

Refrigerating Apparatus.

*(This Invention received Provisional Protection, but notice to proceed with the application for Letters Patent was not given within the time prescribed by the Act.)*

PROVISIONAL SPECIFICATION left by Charles William Siemens, at the Office of the Commissioners of Patents, with his Petition, on the 29th July 1857.

I, CHARLES WILLIAM SIEMENS, of John Street, Adelphi, in the County of Middlesex, do hereby declare the nature of the said Invention for "IMPROVEMENTS IN REFRIGERATING AND PRODUCING ICE, AND IN APPARATUS OR MACHINERY FOR THAT PURPOSE," to be as follows:—

The Invention relates to freezing and refrigerating by the expansion of air or elastic fluids. The air is first compressed by a cylinder or pump of any suitable construction, by which its temperature is raised, and it is cooled while in the compressed state, and it is then allowed to expand in a cylinder or engine of any suitable construction by which its temperature is lowered. The air thus cooled is brought in contact with the articles to be cooled or frozen, and is then conducted through an interchanger or apparatus by which it is made to cool the compressed air, which enters the interchanger in the opposite direction. The pump for compressing the air is worked by a steam engine or other power, and the engine in which the air expands is made to assist in working the pump. I prefer to connect the steam engine and the air engine and the pump to the same rod or moving part, so as to transmit the power directly from one to the other. If the atmosphere be at 70° Fahrenheit, and the air be heated 50° by the compression, and be then cooled to 70°, and allowed to expand, its temperature will be lowered to about 20°, more or less. This cold air will then enter the interchanger and cool the

---

*Siemens' Improved Apparatus for Refrigerating and Producing Ice.*

---

next portion of compressed air, say to 30°, and will itself be heated say to about 110°, and will pass away into the atmosphere. The compressed air at 30° being allowed to expand, will be cooled to about 20° below zero, and in passing through the interchanger will cool the next portion of compressed air, say to 10° below zero. This on expanding will be reduced to about 60° below zero, and so on. These temperatures are mentioned not as the absolute temperatures, but to shew that the principle of the Invention is adapted to produce an accumulated effect or an indefinite reduction of temperature.

I construct machinery or apparatus for carrying out the Invention by immersing the engine in brine or a solution of chloride of calcium or other suitable fluid which will not congeal at the temperature which it is required to produce. I cause the air, after expanding in the engine, to pass into a series of tubes immersed in the brine or other fluid. These tubes are perforated on their under sides, so that the air passes through the brine in a multitude of streams or bubbles and thus cools the brine; or the air is admitted into a casing surrounding the brine vessel, and allowed to pass through perforations in the sides. The vessel which contains the brine is covered, and the cold air is conveyed from it through the interchanger, which consists of a series of tubes inclosed in a case. The cold air is conveyed through the tubes, while the compressed air passes in the contrary direction through the case or vice versa. The compressed air thus enters warm and passes out cold, while the expanded air enters cold and passes out warm. The water or other liquids or articles to be cooled or frozen, are immersed in the aforesaid brine or other fluid; thus the heat which is continually abstracted from the articles to be cooled or frozen, is carried off by the heated air. This current of heated air may be allowed to escape into the atmosphere, or it may be employed for any purpose for which such a current of heated air may be required. The construction of the interchanger may be varied, or two or more regenerators or respirators filled with wire gauze or metallic plates, or other suitable materials may be employed alternately for the compressed and expanded air. The water or other liquid to be cooled or frozen may also be conducted through tubes in the interchanger, or exposed to the contact of the cold air, so as to cool it down before it enters the vessels in which it is to be frozen. When it is required to supply cold air to a cellar or chamber of any sort, the cold expanded air is conducted into such chamber, and on leaving the chamber it passes through the interchanger as before.

---

LONDON :

Printed by GEORGE EDWARD EYRE and WILLIAM SPOTTISWOODE,  
Printers to the Queen's most Excellent Majesty. 1858.

## Appendix A2: Equations of State

### A2.1. Van der Waals Equation of State

The Van der Waals equation of state is mainly applicable for obtaining closed form solutions, and for describing the basic behavior, trends and phenomena, if one is willing to tolerate less accurate quantitative results.

$$P = \frac{R \cdot T}{v - b} - \frac{a}{v^2} \quad (\text{A2.1})$$

$$Z = 1 + \frac{b \cdot \rho}{1 - b \cdot \rho} - \frac{a \cdot \rho}{R \cdot T} \quad (\text{A2.2})$$

$$\Pi = \frac{8\Theta}{3\Phi - 1} - \frac{3}{\Phi^2} \quad (\text{A2.3})$$

$$a = \frac{27}{64} \frac{R^2 T_C^2}{P_C} = \frac{9}{8} R T_C v_C = 3 P_C v_C^2 \quad (\text{A2.4})$$

$$b = \frac{1}{8} \cdot \frac{R \cdot T_C}{P_C} = \frac{v_C}{3} \quad (\text{A2.5})$$

$$P_C = \frac{a}{27b^2} \quad (\text{A2.6})$$

$$T_C = \frac{8a}{27bR} \quad (\text{A2.7})$$

$$Z_C = \frac{3}{8} \quad (\text{A2.8})$$

$$Z^3 - \left( \frac{\Pi}{8\Theta} + 1 \right) Z^2 + \frac{27\Pi}{64\Theta^2} Z - \frac{27\Pi^2}{64\Theta^3} = 0 \quad (\text{A2.9})$$

### A2.2. Peng-Robinson Equation of State

The Peng-Robinson equation of state provides a cubic EOS which may be considered as an advanced enhancement of the Van der Waals EOS. It also enables closed form expressions with much higher quantitative accuracy.

$$P = \frac{R \cdot T}{v - b} - \frac{a(T)}{v \cdot (v + b) + b \cdot (v - b)} \quad (\text{A2.10})$$

$$a(T) = 0.45724 \frac{R^2 \cdot T_C^2}{P_C} \cdot \alpha(T) \quad (\text{A2.11})$$

$$b = 0.07780 \frac{R T_C}{P_C} \quad (\text{A2.12})$$

$$\alpha^{1/2} = 1 + m \cdot \left[ 1 - (T/T_C)^{1/2} \right] \quad (\text{A2.13})$$

Formally, the acentricity factor of a gas is defined on the basis of the saturation curve as proposed by Pitzer,

$$\omega = -1 - \log_{10} \frac{P_S(T/T_C = 0.7)}{P_C} \quad (\text{A2.14})$$

where  $P_S$  is the saturation pressure. On the logarithmic scale, it describes the extent that the saturation pressure deviates from that of the non-quantum noble gases argon, krypton and xenon, for which it vanishes,  $\omega = 0$ . The acentric factor is implemented into the equation through,

$$m = 0.37464 + 1.5422 \omega - 0.26992 \omega^2 \quad (\text{A2.15})$$

$$A = \frac{a \cdot P}{R^2 \cdot T^2} \quad (\text{A2.16})$$

$$B = \frac{b P}{R T} \quad (\text{A2.17})$$

A proper rearrangement leads to the expressions,

$$T \cdot \frac{da(T)}{dT} = -m \cdot a(T) \cdot \left( \frac{T}{\alpha \cdot T_C} \right)^{1/2} \quad (\text{A2.18})$$

$$Z^3 + C_2 \cdot Z^2 + C_1 \cdot Z + C_0 = 0 \quad (\text{A2.19})$$

$$C_1 = A - 3B^2 - 2B \quad (\text{A2.20})$$

$$C_2 = B - 1 \quad (\text{A2.21})$$

$$C_3 = B^3 + B^2 - A \cdot B \quad (\text{A2.22})$$

$$Z_C = 0.307 \quad (\text{A2.23})$$

### A2.3. Virial Equation of State (Proposed by K. Onnes in 1912)

There are two versions of the Virial EOS, one expanded by pressure and the other expanded by density.

$$\begin{aligned} Z = \frac{P \cdot v}{R \cdot T} &= 1 + B \cdot \rho + C \cdot \rho^2 + D \cdot \rho^3 + \dots \quad \equiv \\ &\equiv 1 + B' \cdot P + C' \cdot P^2 + D' \cdot P^3 \dots \end{aligned} \quad (\text{A2.24})$$

The coefficients of these two,  $B(T)$ ,  $C(T)$ ,  $D(T)$  etc. are solely temperature dependent, as are  $B'(T)$ ,  $C'(T)$ ,  $D'(T)$  etc., which are related to each other by the equations,

$$B' = \frac{B}{R \cdot T} \quad (\text{A2.25})$$

$$C' = \frac{(C - B^2)}{(R \cdot T)^2} \quad (\text{A2.26})$$

$$D' = \frac{D + 2B^3 - 3B \cdot C}{(R \cdot T)^3} \quad (\text{A2.27})$$

$$\frac{dB'}{dT} = \frac{1}{R \cdot T} \left( \frac{dB}{dT} - \frac{B}{T} \right) \quad (\text{A2.28})$$

$$\frac{dC'}{dT} = \frac{1}{(R \cdot T)^2} \left( \frac{B^2 - C}{T} + \frac{dC}{dT} - 2B \frac{dB}{dT} \right) \quad (\text{A2.29})$$

The van der Waals equation of state expanded by density is,

$$B = b - \frac{a}{RT} \quad (\text{A2.30})$$

$$C = b^2 \quad (\text{A2.31})$$

$$D = b^3 \quad (\text{A2.32})$$

### A2.4. Truncated Virial Equation of State

$$Z = \frac{P v}{R T} = 1 + B' P = 1 + \frac{B P}{R T} \quad (\text{A2.33})$$

### A2.5. Interrelating the Third Parameter of the Principle of Corresponding States

$$Z_C = 0.29056 - 0.08775 \cdot \omega \quad (\text{A2.34})$$

The quantity  $Z_C$  ranges for most of the substances from 0.22 to 0.30. A more complex molecule with a larger positive value of  $\omega$  has a smaller value of  $Z_C$ .

Riedel proposed another acentricity factor based on the saturation line, but at the critical state

$$\alpha_C = \frac{d(\log P_S)}{d(\log T_S)} \quad @ (T_C, P_C) \quad (\text{A2.35})$$

where  $P_S$  is the saturation pressure corresponding to the saturation temperature,  $T_S$ .

Riedel's acentricity factor is related to Pitzer's acentricity factor by,

$$\alpha_C = 5.811 + 4.919\omega \quad (\text{A2.36})$$

## Appendix A3: Parameters of Gases

		$M$ [g/mol]	$T_C$ [K]	$P_C$ [MPa]	$T_{BOIL}$ [K]	$T_M$ [K]	$\omega$	$Z_C$
Helium-3	$^3\text{He}$	3.017	3.3	0.1188	3.2		-0.473	0.302
Helium-4	$^4\text{He}$	4.003	5.2	0.227	4.2		-0.365	0.302
Hydrogen	$\text{H}_2$	2.016	33.0	1.30	20.4	13.8	-0.214	0.306
Deuterium	$\text{D}_2$	4.032	38.3	1.66	23.6	18.6	-0.176	0.312
Neon	$\text{Ne}$	20.18	44.4	2.68	27.1	24.6	-0.029	0.311
Nitrogen	$\text{N}_2$	28.01	126.2	3.34	77.3	63.3	0.037	0.290
Carbon monoxide	$\text{CO}$	28.01	132.8	3.45	81.7	68.1	0.051	0.295
Fluorine	$\text{F}_2$	37.997	144.4	5.22	85.0	53.5	0.054	0.288
Argon	$\text{Ar}$	39.948	150.8	4.87	87.3	83.8	0.001	0.291
Oxygen	$\text{O}_2$	32.00	154.6	5.08	90.2	54.4	0.025	0.288
Methane	$\text{CH}_4$	16.04	190.6	4.60	111.7	90.7	0.011	0.286
Krypton	$\text{Kr}$	83.30	209.4	5.51	119.9	115.9	-0.002	0.288
R-14	$\text{CF}_4$	88.005	227.7	3.74	145.2	89.3	0.178	0.276
Xenon	$\text{Xe}$	131.30	289.7	5.82	165.1	161.3	0.004	0.287
Ethylene	$\text{C}_2\text{H}_4$	28.05	282.7	5.11	169.4	104.0	0.087	0.280
Ethane	$\text{C}_2\text{H}_6$	30.07	305.5	4.89	184.5	89.9	0.099	0.288
Nitrous oxide	$\text{N}_2\text{O}$	44.013	309.7	7.22	184.2	182.3	0.165	0.274
Acetylene	$\text{C}_2\text{H}_2$	26.04	308.0	6.20	189.6	192.34	0.184	0.270
R-13	$\text{CClF}_3$	104.46	302.1	3.82	192.0	91.6	0.170	0.278
Carbon dioxide	$\text{CO}_2$	44.02	304.2	7.37		215.7	0.281	0.274
R-13B1	$\text{CF}_3\text{Br}$	148.91	340.2	3.96	215.4	105.2	0.171	0.275
Propylene	$\text{C}_3\text{H}_6$	42.079	364.9	4.62	225.5	87.9	0.141	
Propane	$\text{C}_3\text{H}_8$	44.09	369.8	4.25	231.1	85.5	0.152	0.281
Isobutane	$i\text{C}_4\text{H}_{10}$	58.124	408.2	3.64	261.4	113.6	0.185	0.278
1-butene	$1\text{-C}_4\text{H}_8$	56.11	419.6	4.02	266.9	87.8	0.191	
n-butane	$n\text{C}_4\text{H}_{10}$	58.124	425.2	3.80	272.7	134.8	0.201	

# Index

- A**  
Acentricity factor  
  of Pitzer, 51  
  of Riedel, 51  
Acetylene, 65, 176  
Active magnetic recuperative, 22  
  refrigeration (AMRR), 18, 21, 22  
Adiabatic demagnetization, 16, 18, 22  
Air, 3, 101, 16, 23, 25, 31, 41, 48, 63–65, 68, 80, 81, 84, 104,  
  117–118, 129, 130, 152, 155–156, 158, 160, 169, 172,  
  176, 183, 232, 234, 251, 283, 297, 303, 304, 306, 330  
Alexeev, A., 207, 254, 297, 300, 302, 303, 305, 316, 317,  
  321, 334, 335, 337  
Alfeev, V.N., 297, 300, 301, 309, 315, 316, 320, 339  
Ammonia (NH<sub>3</sub>), 65, 66, 127, 145, 176, 304, 321, 330  
Amoils, S.P., 378, 379  
Argon, 17, 48, 86, 125, 170, 225, 282, 306, 367  
Atrey, M.D., 298  
Auto-cascade, 23, 176, 295, 297, 330, 333, 337  
Availability, 27, 112, 119–120, 160, 300  
Azeotropic mixture, 331
- B**  
Ball Aerospace Joule-Thomson, closed cycle cryocooler,  
  187, 228, 229  
Bellows, 171, 232–236, 238, 239, 242, 243, 247, 248,  
  287, 366, 372, 376  
Bimaterial, 238, 239  
Bimetal, 232, 239, 377  
Bodio, E., 173, 237, 243, 246, 249, 251, 253, 283, 284,  
  297, 298, 342  
Boiarsky, M.J., 297, 301, 303, 304, 306, 323, 335, 336,  
  338, 342  
Boiling point, 70, 17, 20, 51, 78, 80, 87, 90, 91, 93, 95, 98, 99,  
  103, 109, 115, 118, 119, 125–129, 132, 133, 141, 142,  
  144–146, 150–153, 155, 156, 158–160, 167, 171, 177,  
  178, 181–183, 185, 186, 188, 191, 192, 194, 196, 198,  
  199, 204–205, 235, 236, 239, 243, 244, 248, 249, 257,  
  260, 261, 278, 282, 284, 286, 290, 295, 296, 299, 301,  
  302, 304, 306–308, 311, 313–317, 321, 322, 328,  
  330–334, 338, 339, 341, 368, 376–379, 381  
Bottle, gas storage, 142, 182, 196  
Boyle temperature, 58, 59  
Brayton cryocooler, cycle, 16, 17, 19, 21, 24, 182  
Brisson, J.G., 80  
Brodianski, V.M., 297–299, 301, 321, 334  
Bromotrifluoromethane (CBrF<sub>3</sub>), 320  
Bubble point, 307  
Buckingham theorem, 283  
Buller, J.S., 157, 173, 174, 196, 234  
Burger, J.F., 159, 184, 208, 229, 258  
Butane, 312, 316, 321
- C**  
Cailletet, L., 69, 176, 196  
Capacity rate, 70–79, 101, 12, 19–21, 24, 77, 84, 88, 93,  
  100, 103, 279, 299, 300  
  ratio, 79, 12, 14, 17, 20, 21, 94–96, 100, 297  
Capillary tube, 225, 227–229, 246, 251, 329, 335  
Carbon dioxide, 41, 48, 50, 60, 65, 66, 149, 160, 169, 176,  
  195, 236, 255, 260, 302, 304, 320, 361–366, 368, 376, 378  
Carbon monoxide, 50, 60, 66, 118, 143, 315, 338  
Carbon tetrafluoromethane (CF<sub>4</sub>), 90, 98, 99, 126, 127, 129,  
  145, 146, 150, 153–156, 158–160, 173, 182–184, 194,  
  199, 243, 286, 303, 314, 315, 317, 320, 321, 328, 340, 370  
Carnot cycle, efficiency, 26, 27, 118, 119, 180, 181  
Cascade. *See* Staging  
CFD, 372  
Choked flow rate  
  ideal gas, 226, 367–369  
  real gas, 226, 367–369  
Chorowski, M., 169, 173, 243, 251, 252, 283, 298, 304, 317,  
  322, 338  
Claude, G. cycle, 90, 15, 80, 112, 176, 181–182, 206, 330  
Clogging, 31, 190, 194, 227, 230, 232, 242, 301, 302, 332,  
  333, 361–366  
Closed cycle, 70, 23–25, 30–32, 82, 167–169, 171, 175–177,  
  179–182, 186, 201, 202, 205–208, 228, 230, 232, 241,  
  252, 254, 259–261, 289, 295–306, 311, 314, 317, 318,  
  320–329, 332, 335–337, 365, 376–378  
Coefficient of performance, 26, 114–118, 181, 300  
  Carnot, 26, 181  
Coiled coil heat exchanger, 197  
Coiled tube heat exchanger, 244, 245  
Cold air cycle, 3, 80, 81, 84, 117–118  
Cold shield, 193, 200, 201, 257, 288  
Collins, S.C., 15, 80, 206  
  liquefier, 15, 80  
Composition of mixture, 311, 322, 340  
Compressibility, 24, 43, 48, 57–60, 63, 66, 70, 134–136, 138,  
  141, 154–157, 159, 174, 191, 197, 371, 378  
  isothermal, 66, 70, 154  
Compression, 17, 19, 25, 28–32, 41, 80, 82, 114, 116, 117, 120,  
  129, 168–169, 177, 181, 188, 203, 207, 225, 239, 259, 298,  
  300–302, 306, 318, 320, 324, 327, 330, 332, 334–336, 378  
Compressor  
  centrifugal, 207, 306  
  cold, 335  
  diaphragm, 300  
  electrochemical, 169

- Compressor (*cont.*)  
 linear, free piston, 169, 300  
 lubricated, 188, 300–303, 306, 333  
 oil free, 300, 301, 329  
 piston, 17, 24, 69, 169, 300  
 rolling piston, 169  
 sorption, 159, 169, 184, 207–208, 258, 261, 303, 333
- Contamination, vapor impurities, 31, 363, 365, 366
- Cooldown  
 calculation, 97, 148, 380  
 fast, 159, 170–171, 188–201, 239, 247, 248, 250, 251, 257, 260, 285, 291, 333  
 process, 3, 70, 20, 31, 77, 86, 101, 142, 172, 175, 192, 194, 196, 200, 243, 244, 277–283, 285, 287–289, 308, 322, 327, 328, 361, 366, 380, 381  
 similarity, 283–287, 380
- Cooper, L.S., 245, 375
- Corresponding states, the principle of, 44, 45, 51–52, 60, 62, 125, 126, 150, 160, 296, 367–368
- Counter current heat exchanger, 25
- Critical  
 compressibility, 60, 141, 156  
 near critical conditions, 188  
 pressure, 77, 79–81, 133, 135, 156, 167, 169, 183, 204, 207, 337, 366, 368, 376  
 state, 47–50, 60, 67, 68, 136–137, 376  
 temperature, 46, 52–53, 126, 129–132, 139, 141, 144, 151, 159, 235, 296, 298, 312–314, 368, 381
- Cryobiology, 375
- Cryocooler, 3, 41, 77, 125, 167, 225, 277, 295, 361
- Cryo-preservation, 375
- Cryopump, 201
- Cryosurgery  
 devices, 375  
 thawing, 375
- Cryotiger, 301
- Current leads, 250, 303, 322, 337
- Cut-off pressure, 96, 172, 173, 182, 190, 196, 199, 202, 341, 342, 370, 371, 378
- D**
- Dephlagmation, 333
- Deuterium ( $D_2$ ), 21, 48, 50, 52, 53, 61, 62, 65, 66, 127, 133, 134, 145, 146, 160, 183–184
- De Wale, A.T.A.M., 23
- Dewar, 30, 31, 169–171, 176, 190, 193, 198, 237, 238, 246, 248, 250, 253, 254, 261, 277–284, 288, 300, 339, 369, 372–376
- Dew point, 307, 316–317, 366
- Diffusion bonding, 252, 254, 378
- Dilution refrigerator, 22, 23, 25, 126
- Discharge of pressure vessel  
 adiabatic, 69, 155, 157–158, 341, 342, 370, 371  
 fixed orifice, 160, 171, 173–175, 182, 191, 197, 338, 339, 370, 371  
 ideal flow regulation, 157, 174  
 isothermal, 154–158, 189, 324, 339, 342, 370, 371
- Displacement, volumetric, 323, 324
- Dual pressure cycle, 84, 118
- E**
- Effectiveness of heat exchanger, 178
- Efficiency  
 of heat exchanger, 305
- Carnot, 29  
 of compressor, 323  
 Second Law, 27, 120
- Ejector  
 helium, 79  
 hydrogen, 79  
 nitrogen, 207
- Electrochemical compressor, 169
- Encapsulation of cryocooler  
 evacuated (or dewar), 190  
 non evacuated, 190
- Enthalpy  
 excess, 46  
 isothermal difference, 126, 370  
 residual (or departure), 128
- Entropy generation, by  
 counter flow heat exchanger, 13  
 laminar flow, 113  
 shock wave, 114  
 throttling, 112
- Equation of state  
 ideal gas, 41  
 Peng-Robinson, 46, 62, 136–138, 317  
 van der Waals, 41, 54–56, 62–63  
 virial expansion, 43
- Ethane, 48, 65, 70, 116, 118, 129, 149, 303, 311, 312, 315–317, 321, 338, 339, 342
- Ethylene, 48, 65, 70, 116, 176, 181, 236, 255, 258, 330, 376
- Eutectic composition and temperature, 315
- Evaporator, 14, 21, 30, 78–81, 87, 93, 98, 110, 119, 171, 175, 176, 178, 187, 188, 190, 191, 193, 195, 205, 207, 225, 233, 235, 237, 238, 243, 256, 258, 260, 277–282, 290, 298, 305–308, 310, 316–317, 324, 327, 329, 334, 336
- Excess property, 46
- Exergy, 119, 120, 182, 300, 334
- Expander, 3, 90, 15–17, 23–24, 29, 80, 112, 168, 176, 203–207, 237, 239, 329, 336
- Expansivity, thermal, 46–47, 67–68, 70
- F**
- Fanning friction factor, 372, 373
- Fast cooldown, 167, 188–201, 239, 247, 248, 250, 251, 257, 260, 285, 291, 333
- Figure of merit, 27, 118–119, 181
- Filtration, 260, 306
- Finned tube heat exchanger, 171, 200, 240, 245–249, 252
- First Law of thermodynamics, 77, 84, 112
- Flammability, 168, 261, 320
- Flow adjusting mechanism, based on  
 bellows, vapor bulb, 235  
 bi-material, 238, 239  
 bi-metal, 232  
 electromagnet, 240  
 piezoelectric, 242  
 shape memory alloy, 232, 240  
 thermal expansion, 232
- Flow demand cryocooler, 282, 342
- Flow rate  
 cooldown, 242  
 non recuperated (warm), 287  
 recuperated, 288, 366, 368–370  
 regulated, 173, 236, 260, 366  
 steady state, 85
- Fluorine, 48, 60, 66, 143, 315, 320
- Freezing point, 194, 315–317, 375



Freons, 195, 300, 302, 314, 317, 320, 338, 342, 376  
 Friction factor (of fanning), 113–114, 228, 256, 372, 373  
 Fuderer, A., 176, 296, 297, 330, 332–334

## G

Gas purity, 31, 171, 190, 361–366  
 Geist, J.M., 168, 184, 245–247  
 Giaque, W.F., 244  
 Gibbs free energy, 309  
 Gifford-McMahon (GM) cryocooler, 203, 204, 254, 302, 335  
 Gimbals, 31, 184, 195, 206, 336  
 Glass, 25, 170, 193, 238, 250, 254–256, 258–260, 280, 281, 288, 363, 364  
 Gong, M.Q., 23, 192, 252, 253, 298, 305, 322, 329, 333, 334, 337, 338, 342, 378  
 Gorrie, J., 3  
 Gresin, A.K., 297, 305, 322

## H

Halon, 320  
 Hampson heat exchanger, 232  
 Hampson, W., 9, 10, 16, 18, 22, 24, 28, 41, 64, 77–120, 125, 142, 146, 147, 160, 176, 181, 185, 188, 196, 225, 244, 246, 247, 250, 252–255, 277, 286, 288, 295–307, 317, 318, 334–337, 369, 372, 373, 378, 380  
 Hansen, S., 30, 232, 234  
 Heat capacity  
   of cryocooler, 59, 79, 14, 21, 84, 90, 93, 95, 170, 190, 253, 277, 278, 287, 288  
   ideal gas, (zero pressure), 42, 91, 132, 147, 154  
   isobaric, isochoric  
     difference, 42, 91, 179  
     ratio, 11, 17, 21, 94  
   ratio for recuperating streams, 321, 374  
   residual, 139, 140  
 Heat exchanger  
   effectiveness, 48, 70, 97, 101, 170, 190, 244, 245, 249, 250, 253, 254, 289, 290, 300, 372  
   finned tube, 171, 173, 178, 184, 186, 192, 193, 197, 200, 240, 245–249, 252, 256, 300, 379  
   Hampson, 16, 77, 80, 81, 84, 113, 119, 188, 196, 244, 246, 247, 250, 252–254, 286, 288, 372, 373  
   Linde, 16, 24, 77, 80, 84, 113, 119, 188, 196, 231, 244, 253–255, 258, 334, 372, 378  
   matrix, 198, 238, 240, 250, 251  
   Parkinson, 248, 253  
   perforated plates, 244, 250, 252, 255, 260, 378  
   pinch point, 70, 101, 77, 78, 84, 93, 110, 206, 299, 305, 309, 334  
   reversing, 23  
 Heat leak, 12, 172, 173, 190, 193, 237, 238, 242, 249, 250, 254–259, 277, 279, 374  
 Heat load, 48–70, 18–20, 24, 26, 30, 78, 80, 84, 85, 87, 102, 110, 111, 157, 169–171, 173, 175, 178, 186, 187, 190, 202, 232, 233, 241, 244, 277–280, 305, 307–310, 316, 322, 324, 327–329, 331, 334, 336, 370, 371, 381  
 Heat pipe, 376  
 Helium  
   <sup>3</sup>He, 18, 22, 51, 52, 62, 65, 125–126, 159, 160, 183–184, 205, 207–208  
   <sup>4</sup>He, 18, 22, 51, 62, 65, 125–126, 159, 160, 183–184, 204, 205, 207–208  
   <sup>3</sup>He-<sup>4</sup>He mixture, 18, 22  
   He-I, 49, 79, 230

He-II, 46, 49, 67–68, 79, 80, 230  
 J-T inversion states, 42, 49, 50, 54, 56–65, 133  
 Heylandt cycle, 15, 80  
 Hingst, U., 25, 184, 186, 202, 317, 320, 339, 366  
 Holland, H.J., 231, 258  
 Hybrid cryocoolers  
   GM/JT, 203, 204, 206, 207, 301  
   Stirling/JT, 204, 206  
   thermoelectric/JT, 180, 201, 202, 258  
 Hydrocarbons, 24, 62, 65, 125, 132, 300, 302, 304, 306, 317–322, 330, 332–334, 338–340, 342, 361, 365, 366  
 Hydrogen, 14, 19, 41, 48, 52, 60, 61, 63–65, 67, 79, 84, 104–107, 109–111, 126, 127, 129, 133, 134, 137, 138, 143–145, 147, 153, 155, 156, 158–160, 168, 169, 173–175, 178, 183, 184, 192, 196, 207, 208, 226, 227, 229, 230, 236, 249, 251, 253, 257, 259, 303, 320, 321, 339, 361, 367, 369, 380–383  
 Hymatic Inc., 170, 172, 190, 191, 234, 247

## I

Ice, 3, 79, 362, 364, 375, 376, 378, 379  
 Ideal gas, 70, 13, 28, 29, 41, 42, 45, 46, 49, 52, 65, 67–69, 80, 85, 91, 112, 114, 116, 125, 128, 129, 132, 147, 154, 188, 196, 225–229, 367, 368, 370, 371  
 Impurities, vapor, 362, 365  
 Infrared detector, 170, 175, 196, 200–201, 250, 253, 261, 300, 336–337  
 Initiating valve  
   electromagnetic, 297, 300, 335, 381  
   pyrotechnic, 191  
 Interchanger, 3–26, 29, 30, 77, 104, 244, 278, 279  
 Intermolecular forces, 43, 44, 49  
 Inversion of the Joule-Thomson effect  
   differential curve, 61  
   integral curve, 49, 53, 54, 61–65, 83, 137, 141  
   maximum pressure, 61  
   maximum temperature, 53  
   of mixture, 45–46, 80  
   pressure, 42, 44–45  
   quantum gases, 50–52, 62, 129, 133, 155, 160, 178, 303, 320, 380, 381  
   state, 48–49  
   temperature, 42–70  
 Irreversibility, 70, 101, 13, 27, 47, 110, 112, 119, 120, 180, 181, 205, 300, 334  
 Isenthalpic expansion, 16, 23, 46, 50, 61, 62, 68–69, 80, 81, 83, 90, 103, 112, 133, 137, 143, 146, 148, 152, 153, 188, 206, 280, 299, 307, 322, 363, 380  
 Isentropic expansion, 15–17, 20, 21, 31, 32, 67–69, 80, 112, 113, 157–158, 196, 364, 367

## J

Jones, J.A., 184, 204  
 Joule effect, 67  
 Joule, J.P., 70, 41–70, 79, 125, 167, 225, 277, 295, 365  
 Joule-Thomson effect  
   adiabatic, 16–19, 22, 42, 44, 46, 48, 65, 69, 112, 119, 146, 150, 155, 157–158, 228, 341, 342, 370, 371, 380  
   of aerosol, 49  
   coefficient, 42–49, 67, 68, 70, 132, 146, 152  
   differential, 42–44, 64  
   of gases, 21, 31, 67, 145–152  
   integral, 17, 42, 48, 56, 64, 70, 81, 83, 110, 125, 149, 151, 183, 278, 296, 316, 364

- Joule-Thomson effect (*cont.*)  
 isothermal, 42, 45–48, 84, 126, 127, 129, 131, 133,  
 137, 139, 141, 341, 342, 370, 371, 375  
 of liquid, 201, 204, 205  
 of mixtures, 41, 45–46, 48, 309, 311  
 of two phase fluid, 159, 314, 316  
 zero pressure, 44–45, 66
- Joule-Thomson valve  
 adjustable, 239  
 capillary tube, 227–229  
 defrosted, 228, 229, 365  
 fixed orifice, 168, 175, 191, 239, 240  
 needle valve, 238, 240  
 porous plug, 229–230  
 short hole, 229, 240  
 vortex, 230–231
- K**
- Kapitza, P., 15, 23, 80  
 Karman-Nikuradse, 113  
 Keesom, W.H., 67, 176, 330, 332  
 Kelvin, Lord (W. Thomson), 41–42  
 Kittel, P., 31  
 Kleemenko A.P., cycle, 295–297, 302, 329–337, 378  
 Krypton, 31, 48, 50, 60, 67, 90, 98, 116, 127, 129, 131,  
 133, 145, 149, 150, 153, 155, 156, 158, 159, 185, 186,  
 194, 196, 198, 199, 201, 236, 238, 252, 284, 286, 287,  
 302, 317, 320, 368, 370, 379
- L**
- Liquid, 15, 46, 78, 125, 175, 229, 277, 295, 361  
 Lambda point (superfluidity transition), 79  
 Laminar flow, 113, 243, 256, 304  
 Landa, Yu.I., 157, 238, 239, 246  
 Lashmet, P.K., 168, 184, 245–247  
 Latent heat of  
 evaporation, 83  
 sublimation, 126  
 Leidenfrost effect, 375  
 Lennard-Jones intermolecular potential, 45, 58, 64  
 Lethal temperature, 375  
 Linde, C., 16, 24, 64, 80, 231, 244, 253, 254  
 Linde-Hampson  
 cryocooler, 28, 77–120, 297, 299, 300, 335, 380  
 cycle, 21, 77–85, 103, 109, 116, 117, 119, 125, 196, 277,  
 295, 296, 298, 307, 334, 378  
 dual pressure cycle, 84  
 liquefier, 77, 92–93, 188  
 Linde heat exchanger, 24  
 Liquefaction, 70, 17, 20, 21, 28, 30, 64, 80, 81, 83, 89, 91, 93,  
 98–101, 103, 104, 112, 118, 125–126, 143, 145–148,  
 152–153, 158, 160, 176, 177, 181–186, 188, 191, 193,  
 194, 196, 199, 207, 254, 257, 258, 277, 280, 283, 284,  
 286, 288, 289, 297, 298, 311, 324, 330, 334, 336, 339,  
 369, 371, 378, 379  
 Liquefier, air, 23, 176, 330  
 Liquid phase equilibrium, 296, 316  
 Little, W., 184, 194, 199, 207, 255–256, 258, 290, 291, 297,  
 305, 320, 321, 324, 331–333, 337, 338, 378  
 Lockheed-Martin Inc., 257  
 Longworth, R.C., 97, 98, 154, 158, 173, 175, 176, 189–192,  
 194–196, 198, 204, 228, 234, 235, 238, 240, 245, 247,  
 248, 250, 251, 254, 288, 290, 291, 297, 301, 303, 304,  
 321, 329, 335, 337, 361, 363, 372, 377, 379
- Lubrication  
 kind, 169  
 management, 169  
 Luo, E.C., 252, 253, 298, 300–302, 305, 314, 317, 329,  
 333, 336, 338, 378
- M**
- Mach number, 114, 228, 260  
 Magnetic refrigeration, 18, 21–22, 24  
 Maytal, B-Z., 15, 52, 62, 63, 109, 133, 138, 157, 171, 174, 189,  
 191, 192, 207, 225, 230, 243, 246, 280, 284, 307, 309, 315,  
 317, 324, 338, 339, 364, 365, 367, 368, 379, 381  
 Melting point, 251, 315, 316, 320, 334  
 MEMS. *See* Micro Electro Mechanical Systems (MEMS)  
 Methane (CH<sub>4</sub>), 28, 48, 50, 60, 62, 65, 99, 116, 118, 127, 129,  
 131–133, 140, 141, 143, 149, 154, 156, 160, 174, 176, 181,  
 185, 186, 194, 195, 199, 206, 207, 230, 236, 258, 286, 303,  
 304, 315–317, 321, 322, 330, 332, 334, 336, 338–340,  
 342, 367  
 Micro electro mechanical systems (MEMS), 16, 159, 202, 207,  
 255–260, 282, 363–365, 372, 378  
 Miller, F.K., 57, 60, 64  
 Missimer, D., 176, 330, 332–333  
 Mixed refrigerants  
 halogenated hydrocarbons, 340  
<sup>3</sup>He-<sup>4</sup>He, 18  
 hydrocarbons, 304  
 inert gases, 320  
 optimal composition, 321  
 Mixing  
 enthalpy, 338, 341–342  
 volume, 46  
 Mixtures  
<sup>3</sup>He-<sup>4</sup>He mixture, 18  
 hydrocarbons, 304  
 MMR Inc., 256, 297  
 Molecular sieve, 365  
 Mollier (Richard) diagram, 81  
 Multi stage  
 compression, 169  
 cryocoolers, 176–188, 302  
 thermoelectric cooler, 180
- N**
- Natural gas (NG), 48, 61, 62, 176, 181, 303, 304, 322, 330  
 Needle valve, 228, 233–236, 238, 240–243, 247, 248, 372  
 Nellis, G., 207, 260, 297, 302, 303, 316, 322, 337, 374  
 Neon, 15, 24, 48, 50–52, 60, 66, 67, 69, 85, 104–107, 125–127,  
 129, 133, 143–145, 155, 156, 158–160, 168, 171, 174, 175,  
 178, 183, 184, 192, 199, 203, 208, 236, 251, 257, 258, 299,  
 303, 306, 314, 320, 321, 328, 333, 338, 339, 361, 380–382  
 Nernst, W.,  
 NIST (formerly NBS), 65, 66  
 Nitrogen, 17, 41, 85, 125, 168, 225, 279, 299, 361  
 Nitrous oxide (N<sub>2</sub>O), 160, 320, 378  
 Noble gases, 45, 98, 126, 128, 145, 151, 155, 158–159, 367  
 Nucleation, 362–365, 375
- O**
- Oil  
 contamination, 168  
 separator, 301, 302, 323  
 Olszewski, C., 64, 65, 176, 303, 320

- Onnes, H. Kamerlingh, 147, 176  
 Open cycle, 3, 15, 30, 167, 169, 182, 207, 241, 261, 295, 296, 304, 317, 319, 323, 324, 328, 337–339, 376, 377  
 Open cycle cryocooler, 304, 341, 342  
 Open system, 24, 31, 65, 78, 84, 106, 167–168, 201, 305, 327  
 Optimum  
   coefficient of performance, 117  
   composition of mixture, 322, 340  
   enthalpy difference, 321  
   flow rate, 103, 289  
   isenthalpic temperature drop, 278  
   pressure of operation, 83  
   staging, 259  
   temperature distribution, 232  
 Orifice  
   constant, 240  
   variable, 372  
 Oxygen  
   coolant, 120  
   operating JT cooler, 30
- P**  
 Parkinson, D.H.  
   heat exchanger, 248, 253  
 Peng-Robinson (equation of state), 46, 62, 136–138, 317  
 Pfothenauer, J.M., 24, 62, 322, 337  
 Phase diagram, 317  
 Phase equilibrium  
   liquid-liquid, 49  
   liquid vapor, 51, 306, 311, 316–317  
   solid-liquid-vapor, 311, 314  
 Phase separator, 175, 295–297, 302, 304, 330–335, 378  
 Philips cryocooler. *See* Stirling (cycle) cryocooler  
 Photolithographic heat exchanger, 254  
 Pictet, R., 176, 184  
 Piezoelectric  
   actuator, 242  
   compressor, 259  
 Pinch point, 70, 79, 101, 11, 20, 77, 78, 84, 93, 109, 206, 299, 305, 307–309, 315, 334  
 Plug formation. *See* Clogging  
 Porous metal, 229, 252, 260  
 Porter, A.W., 50, 56, 57, 64, 65  
 Prandtl-Meyer expansion waves, 225  
 Precooling. *See* Staging  
 Pressure  
   regulation, 175  
   source, 31, 146, 167–168, 185, 194, 248, 262, 377, 381  
 Principle of corresponding states, 44, 45, 52, 60, 62, 125, 141, 160, 282, 367–368  
 Probe, cryosurgical, 160, 251, 260, 302–303, 326, 337, 361, 375–378, 381–382  
 Propane, 48, 65, 176, 181, 199, 303, 304, 311, 312, 315–317, 321, 330, 338, 339, 342  
 Pulse tube cryocooler, 17, 69, 180, 207, 335, 336  
 Purification, 160  
 Purity of gas, 190
- Q**  
 Quack, H., 13, 15, 206, 207, 297, 302, 335, 372  
 Quantum gases, 50–52, 62, 129, 133, 155, 160, 177, 178, 183–184, 192, 303, 313, 314, 320–321, 333, 380, 381
- R**  
 Radebaugh, R., 14, 202, 229, 252, 297, 309, 321, 337, 378  
 Radiation detectors, 337  
 Radiation shield, 193  
 Ravex, A., 297  
 Recuperation, 23, 77, 79, 80, 83, 85–93, 95–99, 103, 109, 117, 119, 120, 142, 158, 170, 192, 278, 297–299, 303, 304, 306–308, 331, 337, 372  
 Recuperator, 90, 77, 157, 177, 225, 278, 295, 364  
 Refrigerants  
   R-14, 182, 183, 314, 320  
   R-15, 149, 314, 320, 328  
   R-16, 129, 131  
   R-13B3, 302, 320  
 Refrigeration, 3, 41, 101, 171, 261, 289, 301, 376  
 Regenerator, 90, 101, 14–16, 23, 168, 169, 201, 258, 297, 306, 377  
 Reservoir, of gas, 30, 61, 295  
 Residual properties  
   enthalpy, 127–128, 133, 136, 140  
   entropy, 63  
   heat capacity, 137  
 Revers Brayton cryocooler, 16, 17, 19, 21, 24, 182  
 Reversibility  
   endo-reversible cryocooler, 26, 182  
   exo-reversible cryocooler, 26  
 Reynolds number, 113, 193, 373  
 Roebuck, J.R., 41, 45, 48, 52, 64, 65, 67, 132  
 Rubinsky, B., 376, 379
- S**  
 Satellite (helium) cooler, 22  
 Saturated  
   liquid, 53, 117, 235  
   vapor, 53, 81, 83, 87  
 Scurlock, R., 253  
 Second Law of Thermodynamics, 20, 30, 77, 109, 114–120  
 Shape memory alloys (SMA), 232, 240, 241  
 Shock wave, 113, 114, 225, 227–229, 364  
 Siemens, W. (1823–1883), 3–59, 79, 101, 16  
 Silica gel, 258  
 Silicon, 242, 255–258  
 Silver, 192, 199, 245, 246, 250  
 Similarity of  
   cooldown periods, 283–287  
   heat transfer area, 284  
 Simon, F.E. (1893–1956)  
   cooling effect, 196  
   liquefier, 69  
 Skertic, M.M., 191, 196, 228, 242, 243, 245  
 SMA. *See* Shape memory alloys (SMA)  
 Solid cryogen refrigerator, 79  
 Solvay cryocooler, 24  
 Sonic flow, 363  
 Sorption cryocoolers, 306  
   bi-directional, 168  
   uni-directional, 168  
 Space cryocooler, 365  
 Specific heat, 14, 21, 42, 78, 83, 90–93, 96, 97, 103, 109–111, 114, 137, 140, 147–149, 192–194, 199, 289, 299, 307, 308, 321, 323, 374, 381  
 Speed of sound, 45, 54, 68, 225, 228, 367  
 SQUID, 24, 201, 335, 336

- Staging  
 of cryocoolers, 167, 177–181, 186–188  
 optimum, 180, 182–184  
 parallel, 179–180  
 serial, 180, 181
- Stagnation enthalpy, 69–70, 364
- Stanford University, 255
- Stephens, S., 182, 234
- Stirling (cycle) cryocooler, 70, 21, 24–25, 42, 69, 110, 201, 204, 206, 335, 336
- Strobridge, T.R., 206
- Sublimation, 126, 175, 176, 362
- Superfluid helium, 49, 79, 126, 230
- T**
- Terahertz sensors, 259
- Ter Brake, H.J.M., 208, 243, 258, 336, 372
- Thermal conductivity, 193, 199, 244–246, 250–252, 255, 257
- Thermal diffusivity, 192, 193, 199, 281
- Thermal expansion, 231, 232, 237–240, 242, 243
- Thermal imaging system, 260
- Thermal load, 170, 194, 235
- Thermal mass, 189, 192, 193, 196, 198, 199, 233, 235, 237, 244, 247, 250, 278, 284, 288, 291
- Thermal storage device, 170, 175
- Thermodynamics  
 First Law, 77, 84, 87, 112  
 Second Law, 101, 20, 26, 30, 77, 109, 114–120  
 Third Law, 14
- Thermoelectric cooler, 178, 180, 201, 202, 258
- Thomson effect. *See* Joule-Thomson effect
- Throttle. *See* Joule-Thomson valve
- Throttling  
 laminar friction, 229  
 supersonic, 227  
 turbulent friction, 228
- Timmerhaus, K., 66, 254, 373
- Triple point, 66, 79, 98, 126–128, 158, 160, 175, 196, 315–317, 320, 362
- Turbulent flow, 113, 335
- Twente University, 258–259
- V**
- Valve, Joule-Thomson, 205, 241
- Van der Waals gas, 43–44, 47, 55, 58, 59, 62, 66–68, 136, 138, 139, 142
- Vapor compression cycle, 25, 298, 302
- Vapor pressure, 159, 160, 175, 204, 205, 236, 331, 362, 364
- Venkatarathnam, G., 250, 259, 298, 304, 305, 329
- Venturi, 199, 260
- Vessel, pressure, 154, 155, 190, 191, 199, 249, 305
- Virial expansion of equation of state, 43
- Viscosity, 113, 243, 251, 304
- Volumetric  
 cooling content, 324  
 efficiency, 323, 324, 329
- Vortex  
 throttle, 230, 231, 364, 365  
 tube, 18, 23
- Vuilleumier cryocooler, 17
- W**
- Wade, L., 363
- Walker, G., 204, 231, 232, 237, 243, 244, 247, 261, 365
- Water vapor, 49, 169, 337, 363, 365, 366
- Wick storage of liquid, 175
- Witkowski, A.W., 56, 63–64
- Work, 15–17, 22, 24, 26–29, 43, 65, 67, 69, 79–80, 84, 112–114, 116, 118–120, 129, 147, 176, 181, 182, 188, 196, 197, 203–205, 207, 229, 238, 300, 321, 375, 379  
 useful, 27, 112, 119, 120
- X**
- Xenon, 48, 50, 60, 67, 116, 133, 136, 149, 152, 155, 159, 201, 258, 320
- X ray detector, 337
- Y**
- Yield of liquefaction, 81, 83, 89, 93, 98–101, 103, 104, 152–153, 160, 185, 191, 277, 280, 371
- Z**
- Zeotropic mixture, 320, 331
- Zero pressure  
 heat capacity, 150  
 Joule effect, 67  
 Joule-Thomson effect, 44–45