Maplesoft
Maple™ 计算书与计算管理
热工计算应用

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Mathematics • Modeling • Simulation

Maple™热工计算

热工计算背景

冰箱、空调、余热回收、汽轮机、核电等，热工影响着生活的方方面面。

热工计算多种多样，包括：

- 热动力学热传导建模
- 计算热传递效率
- 传热、冷却系统中的参数优化
- 热流体的微分方程计算
- 模拟蒸汽压缩制冷循环中的热流
- 模拟热交换器的集总参数模型
- 计算空气变为人体舒适区所需的热量变换
- 找到最大化再生朗肯循环效率的参数
- 研究不同的流体和工艺参数如何影响有机朗肯循环的效率

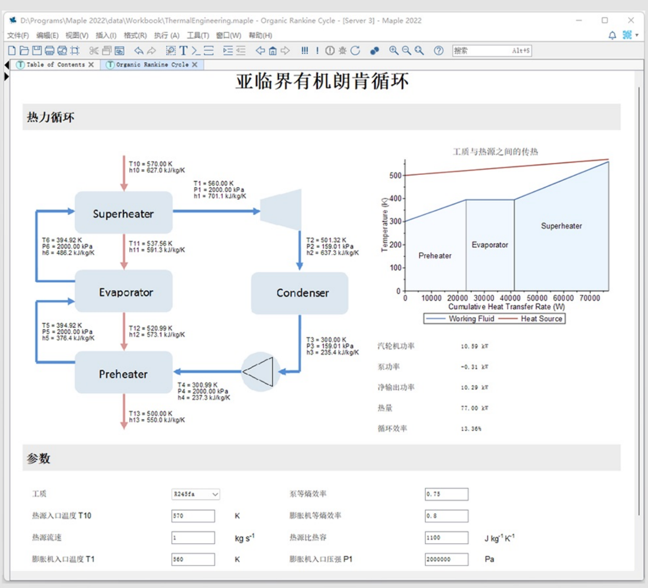

Figure 1. Deployment of an Organic Rankine Cycle application

为了建模和计算这些系统，热工程师需要一些科学概念：

- 热力学，例如
  - 热力学基本定律
  - 焓，熵和比热容的概念
- 流体力学，例如
  - 伯努利定律
  - 泵头和管道摩擦
- 传热与传质
  - 能量守恒定律
    - 传热系数
    - 集总参数建模

此外热能工程师还需要用到一些实际工具：

- 数学，例如
  - 优化
  - 求根
  - 插值和外推
- 计算，例如
  - 编程和脚本
  - “活”的电子计算文件
  - 可视化和图表
  - 应用开发和部署

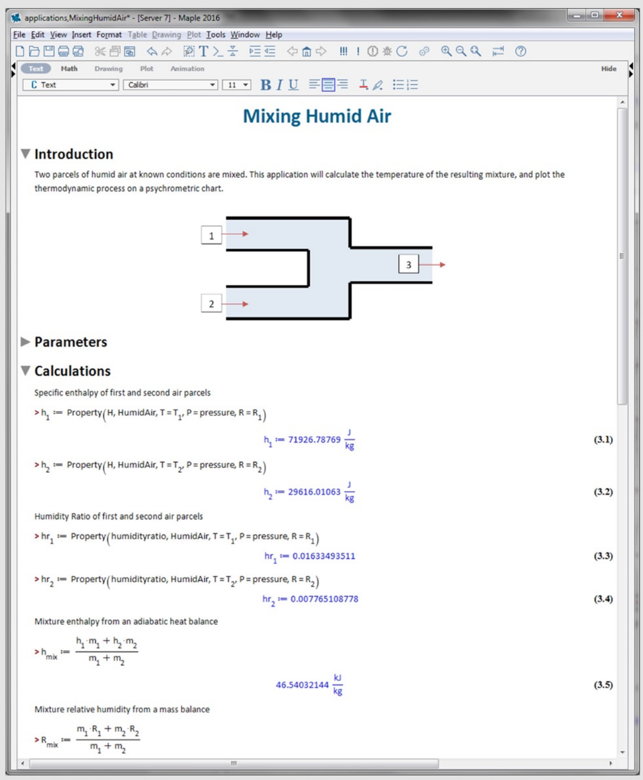

Figure 2. Documenting an analysis

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工具对比

	Fluid Properties	States	Documentation Features	Math	Fluid Property Visualizations	Units	Deployment
Maple	Built-in Locally stored Pure fluids and mixtures	Arbitrary	Full	Numeric & symbolic	Built-in P-h and psychrometric charts Tools for custom charts (e.g. T-s etc.)	Yes	Free to desktop and web
Mathematica®	Built-in but needs internet access Pure fluids only	Temperature and pressure only	Full	Numeric & symbolic	No built in charts Tools for customized charts	Yes	Free to desktop
EES -Engineering Equation Solver	Built in Locally stored Pure fluids and mixtures	Arbitrary	Partial	Numeric only, limited	Built-in T-S, T-v, P-v, P-h, h-s, T-h charts Limited tools for custom charts	Yes	Free to desktop
MATLAB®	Via add-on	Determined by add-on	Partial	Numeric, & symbolic via an add-on	No built-in plots Tools for custom charts	No	Paid to desktop
Mathcad®	Via add-on	Determined by add-on	Full	Numeric and symbolic, both limited	No built-in plots Limited tools for customized charts	Yes	Paid to web
Excel®	Via add-on	Determined by add-on	Partial	Numeric only, limited	No built-in plots Limited tools for customized charts	No	Paid

Table 1. Survey of calculation tools used for thermal engineering calculations

Maple 软件中的相关函数包

· ThermophysicalData –包含一系列计算热物理、热力学、热化学属性的函数。使用【CoolProp Library】，以及【NASA Glenn Coefficients】计算热力学属性
· DEtools – 求解常微分方程的函数包
· PDEtools – 求解偏微分方程的函数包
· ScientificConstants – 科学常数函数包
· Optimization – 参数优化函数包
· Plots – 绘图函数包
· Units – 单位计算函数包
· Tolerances – 公差函数包

流体属性数据库CoolProp

Maple 中的 ThermophysicalData 热物性数据函数包，基于开源物性库 CoolProp，可以使用函数提取热物特性数据。相比传统的使用图表或者查表的方式更加快捷、准确、不容易出错。

CoolProp 库是由 C++ 开发的常用工质热物性计算库，是开源免费物性库。该库包括：
· 122种纯流体和近纯流体状态方程和传输物性方程
· 使用高精度霍尔姆兹自由能公式计算的混合物性
· 40多种不可压缩流体、溶液和高精度湿空气焓湿计算程序

通过该函数包中的数据，可以实现：
· 模拟热力学循环中的热流
· 计算太阳能加热系统的效率
· 使用集中参数模拟换热器
· 优化涡轮机的性能
· 生成特定的焓湿图和压焓图等
该函数包是单位感知的，可以与 Maple 中的数值求解器、优化求解器、微分方程求解器等一起使用。

Maple 中的 ThermophysicalData 函数包，示例：
with (ThermophysicalData):

Figure 3, 二氧化碳在指定压力和焓下的温度：

> Property(temperature, pressure = 6bar, massspecificenthalpy = $5 \cdot 10^5 \, J \, kg^{-1}$, "carbondioxide")

296.9109661 K

Figure 3. 二氧化碳在指定压力和焓下的温度

Figure 4, 在指定的温度和压力下，氦和氮的 30%–70% 摩尔混合物的密度

> Property(density, temperature = 293 K, pressure = 1atm, "helium[0.3]&nitrogen[0.7]")

$0.8652903239 \, \frac{kg}{m^3}$

Figure 4. 氦和氮的 30%-70% 摩尔混合物的密度

Figure 5, 获取R134a的密度属性

> Property(density, temperature = 260 K, pressure = 6 MPa, R134a)

$1354.788341 \, \frac{kg}{m^3}$

Figure 5. 获取R134a的密度属性

Figure 6, 计算任意流体混合物的属性

Property("D", temperature = 300K, pressure = 101325Pa, "HEOS::Methane[0.042]&Ethane[0.845]&nButane[0.028]&Pentane[0.085]")

$1.387544941 \, \frac{kg}{m^3}$

Figure 6. 计算任意流体混合物的属性

Figure 7, 生成PHT图
PHTChart ("nitrogen")

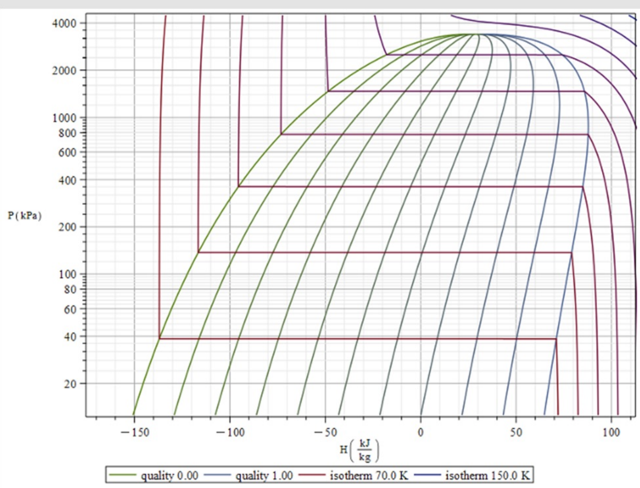


Figure 7. PHTChart ("nitrogen")

Figure 8, 生成湿度图
PHTChart ("nitrogen")

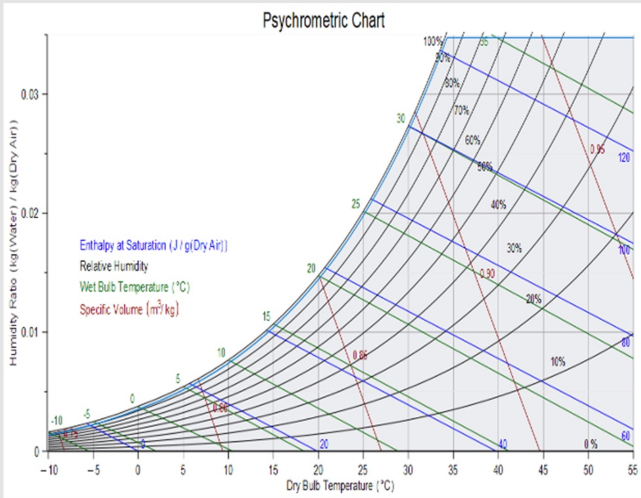


Figure 8. PHTChart ("nitrogen")

计算功能 – 单位计算

Figure 9, Maple 支持单位计算。

ρ := Property(density, temperature = 310 K, pressure = 14.7 psi, water)

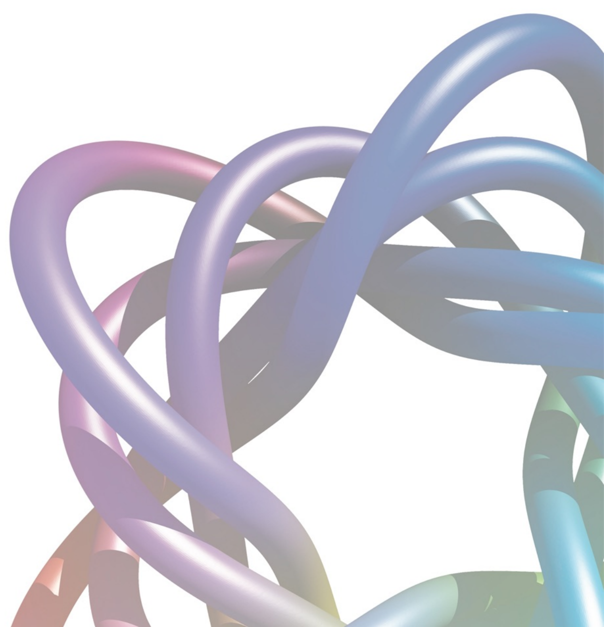
$\rho := 993.3836403 \, \frac{kg}{m^3}$

$v := 2.5 \, inch^3$:

$m := \rho \cdot v$

$m := 0.04069660323 \, kg$

Figure 9. Units tracking



工质热物性数据库

Figure 10, 稳态热和质量平衡是热能工程中的基本概念，但通常只涉及简单的数学运算。

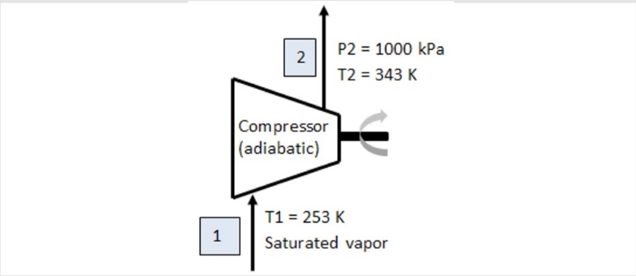


Figure 10. Compressor with known entry and exit states

Figure 11, 以 R134a 为介质的压缩机，已知输入和输出条件。

> h1 := Property(H, temperature = 253 K, Q = 1, R134a)

$$h1 := 3.864615358\,10^{5}\,\frac{J}{kg}$$

> h2 := Property(H, temperature = 343 K, pressure = 1000kPa, R134a)

$$h2 := 4.518442441\,10^{5}\,\frac{J}{kg}$$

Work done by the compressor

> workCompressor := h1 − h2

$$workCompressor := -65382.7083\,\frac{J}{kg}$$

Figure 11. Maple calculation of the work done by a compressor

方程求解

Figure 12, 求解一组隐式方程组，描述求解流体通过绝热膨胀阀的流动。

> with(ThermophysicalData) :

> fluid := "R717" :

Temperature, pressure and velocity at inlet

> $T_{in} := 310$:

$P_{in} := 11 \cdot 10^{5}$:

$v_{in} := 10$:

Pressure at outlet

> $P_{out} := 2 \cdot 10^{5}$:

Enthalpy and density at inlet

> h_{in} := Property(massspecificenthalpy, $T = T_{in}$, $P = P_{in}$, fluid);

ρ_{in} := Property(density, $T = T_{in}$, $P = P_{in}$, fluid);

$$h_{in} := 1.65559094731116970\,10^{6}$$

$$\rho_{in} := 8.15132757401520891$$

$$\rho_{in} := 8.15132757401520891$$

> eq1 := h_{out} = Property("massspecificenthalpy", "temperature" = T_{out}, "pressure" = P_{out}, fluid) :

eq2 := ρ_{out} = Property("D", "temperature" = T_{out}, "pressure" = P_{out}, fluid) :

First law of thermodynamics

> $eq3 := h_{in} + \frac{v_{in}^{2}}{2} = h_{out} + \frac{v_{out}^{2}}{2}$:

Conservation of mass

> $eq4 := v_{in} \cdot \rho_{in} = v_{out} \cdot \rho_{out}$:

> fsolve({eq1, eq2, eq3, eq4})

$$\{T_{out} = 285.0179004,\ h_{out} = 1.654113289\,10^{6},\ v_{out} = 55.27490598,\ \rho_{out} = 1.474688637\}$$

Figure 12. Solving implicit equations in Maple

微分方程求解

Wall heat balance

> $$pde1 := \frac{\pi}{4}\left(D_o^{2} - D_i^{2}\right) Cp_w \rho_w \frac{\partial}{\partial t} T_w(x,t) = U_t \cdot \pi D_i \left(T_t(x,t) - T_w(x,t)\right) - U_s \pi D_o \left(T_w(x,t) - T_s(x,t)\right) + k_w \frac{\pi}{4} \cdot \left(D_o^{2} - D_i^{2}\right) \frac{\partial^2}{\partial x^2} T_w(x,t) :$$

Tube-side heat balance

> $$pde2 := \rho_t Cp_t \frac{\pi}{4} D_i^{2} \frac{\partial}{\partial t} T_t(x,t) = -Cp_t F_t \frac{\partial}{\partial x} T_t(x,t) - \pi D_i U_t \left(T_t(x,t) - T_w(x,t)\right) :$$

Shell-side heat balance

> $$pde3 := \rho_s Cp_s \frac{\pi}{4}\left(D_{is}^{2} - D_o^{2}\right) \frac{\partial}{\partial t} T_s(x,t) = Cp_s \cdot F_s \cdot \frac{\partial}{\partial x} T_s(x,t) + \pi D_o U_s \left(T_w(x,t) - T_s(x,t)\right) :$$

Discretize the PDEs into ODEs with a central difference approximation

> res := disc({pde1, pde2, pde3}, {T_t, T_s, T_w})

$$res := \frac{\pi\left(-D_i^{2} + D_o^{2}\right) Cp_w \rho_w \dot{T}_{w_i}(t)}{4} = U_t \pi D_i \left(T_{t_i}(t) - T_{w_i}(t)\right) - U_s \pi D_o \left(T_{w_i}(t) - T_{s_i}(t)\right) + \frac{k_w \pi \left(-D_i^{2} + D_o^{2}\right)\left(T_{w_{i+1}}(t) - 2\,T_{w_i}(t) + T_{w_{i-1}}(t)\right)}{4\ deltaX^{2}},$$

$$\frac{\rho_s Cp_s \pi \left(D_{is}^{2} - D_o^{2}\right) \dot{T}_{s_i}(t)}{4} = \frac{Cp_s F_s \left(T_{s_{i+1}}(t) - T_{s_{i-1}}(t)\right)}{2\ deltaX} + U_s \pi D_o \left(T_{w_i}(t) - T_{s_i}(t)\right), \frac{\rho_t Cp_t \pi D_i^{2} \dot{T}_{t_i}(t)}{4} = -\frac{Cp_t F_t \left(T_{t_{i+1}}(t) - T_{t_{i-1}}(t)\right)}{2\ deltaX} - U_t \pi D_i \left(T_{t_i}(t) - T_{w_i}(t)\right)$$

Figure 13. Discretizing PDEs into ODEs with Maple

符号计算 – 偏微分方程离散为差分方程计算

Fugure 13, 许多热交换过程是用偏微分方程来描述，例如逆流热交换器中的温度动态，这些偏微分方程离散为常微分方程用于集总参数分析。

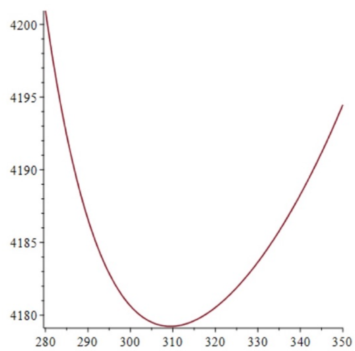
Figure 14, 流体属性可以作为温度的函数，在离散化前可以代入PDE中。

```
> Cp_t := Property("C", "pressure" = pNom, "temperature" = T_t(x, t), fluid1) :
  Cp_s := Property("C", "pressure" = pNom, "temperature" = T_s(x, t), fluid2) :
> ρ_t := Property("D", "pressure" = pNom, "temperature" = T_t(x, t), fluid1) :
  ρ_s := Property("D", "pressure" = pNom, "temperature" = T_s(x, t), fluid2) :
```

Figure 14. Fluid properties as a function of temperature for the countercurrent heat exchanger model

Figure 15, 优化

```
> Cp := T→Property(C, temperature = T, pressure = 101325, water) :
> plot(Cp, 280..350)
```




```
> Minimize(Cp, 280..390)
                    [4179.23671956654, [309.399693997860]]
```

Figure 15. Calculating the minimum isobaric specific heat capacity of water

```
> Cp := t→Property("C", "temperature" = t, "pressure" = 101325, "water") :
> m := 1.0 :
  Q := 500 :
> de := m·Cp(T(t))·d/dt T(t) = Q, T(0) = 280 :
> res := dsolve({de}, numeric) :
> plots:-odeplot(res, 0..100)
```

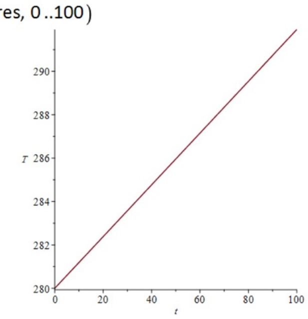


Figure 16. Simulating a differential equation in Maple with varying fluid properties

```
> res := dsolve({ODEs, ic}, numeric, known = {Property}, range = 0..T_final, output = listprocedure) :
> assign(seq(Ts || i = subs(res, T[s][i](t)), i = 1..N)) :
  assign(seq(Tt || i = subs(res, T[t][i](t)), i = 1..N)) :
> p1 := odeplot(res, [t, T_t[N](t)], t = 0..T_final, legend = ["Tube-side Exit Temperature"]) :
  p2 := odeplot(res, [t, T_s[1](t)], t = 0..T_final, legend = ["Shell-side Exit Temperature"], color = blue) :
> display(p1, p2, legendstyle = [font = [Arial]], labels = ["Time (s)", "Temperature (K)"], labeldirections
    = [horizontal, vertical], labelfont = [Arial])
```

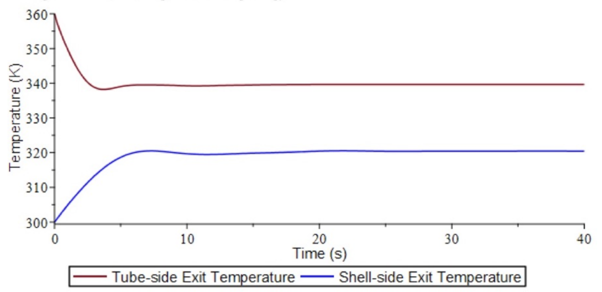


Figure 17. Simulating a lumped parameter model of a heat exchanger in Maple

热工计算的可视化

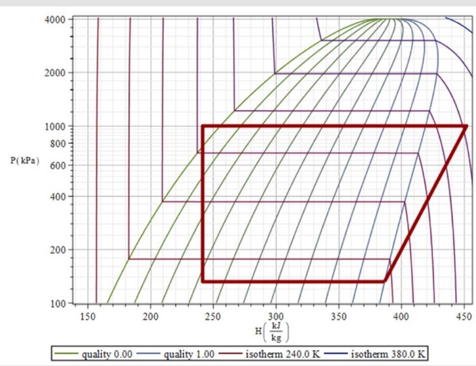


Figure 18. 压焓温度表

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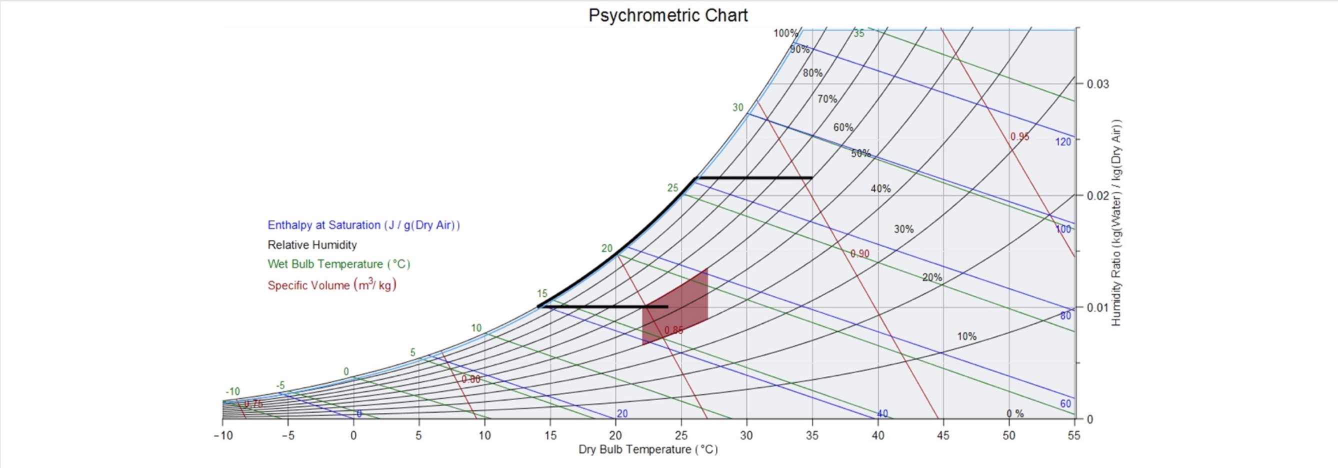

Figure 19. 焓湿图

计算模板部署和分享

多种部署工具和方案：

- Maple（桌面程序）
- MapleNET（局域网或互联网）
- 免费阅读器 MaplePlayer

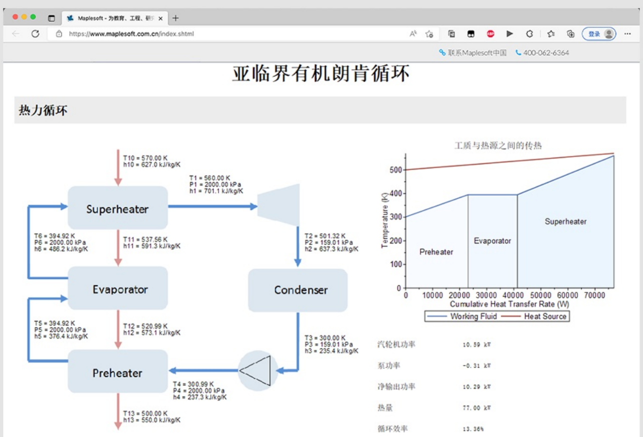

Figure 20. B/S架构下使用网页浏览器打开在线计算书

Maple中热工应用案例库

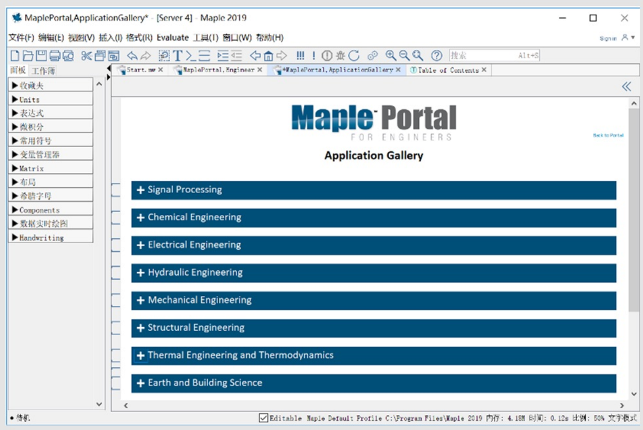

Figure 21. 案例库

计算书Workbook

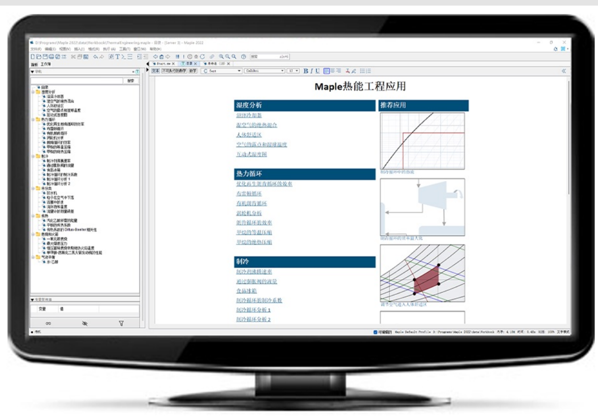

Figure 22. 计算书Workbook

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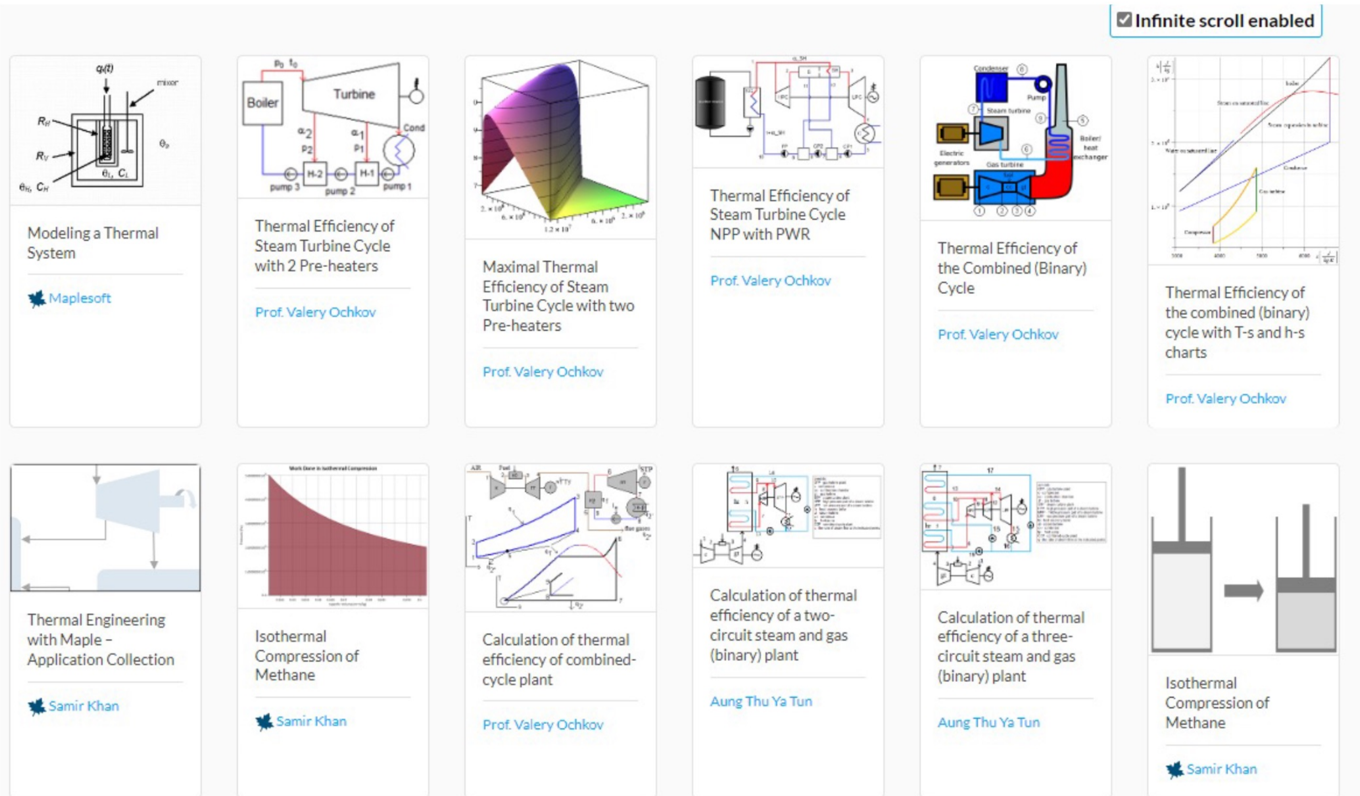
热工计算示例



示例下载：
https://cn.maplesoft.com/Applications/Search.aspx?q=thermal

- 蒸汽压缩制冷循环分析
- 再生朗肯循环的效率优化
- 调节空气进入人体舒适区
- 通过膨胀阀的流体计算
- 潮湿的空气混合
- 空气流经平板时的传热系数
- 汽化乙醇所需的能量
- 组合循环的热效率
- 带压水堆的汽轮机循环型核电厂热效率
- 带有 2 个预热器的汽轮机循环的热效率
- 三回路蒸汽和燃气装置热效率的计算
- 甲烷的等温压缩
- 具有 T-s 和 h-s 图的组合循环的热效率等

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