Case Study 11
Fuel flow in a distribution network
A small airfield currently has two ramps handling chartered airline aircraft and rural cargo carriers. Both ramps use over wing refueling systems and have two refueling points per ramp. You have been contracted as consultant to design the upgrade to the refueling system in support of planned expansions and the new runway at the airfield.
To enable the airfield to handle larger domestic airliners, a new refueling system for the airline ramp is needed. The current over wing system is too slow for larger planes and airfield management wants to investigate the installation of a SPPR-based system. (SPPR = single point pressurized refueling). The current over-wing system operates at 1 atm (100 kPa), while SPPR operates at 50 psi (345 kPa).

Your tasks are:

➢ Pressurize the cargo ramp refueling points (assume that the installed piping is rated to handle the higher pressures)

➢ Replace the control valve with a booster pump and use Flownex Designer to determine the pump speed for a delivery rate of 240 kg/s to the airline ramp. The flow rate to the cargo ramp should be 90 kg/s with the valve fully open.

➢ British clients of your company would like a quotation on the same system for a private Royal airfield. Use the unit conversion functionality to prepare the results.
Phase 1: Domestic ramp upgrade

For this case study, previously configured networks will be used as starting point for the modifications. The completed network of one phase is also the starting network for the next phase of the problem, so that users can skip ahead by starting with the appropriate network.

The initial network contains the current configuration of the airfield: the pump farm with one pump and the cargo and charter ramps with their control valves.

The fluid used in this case study represents jet fuel, with the following properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>850</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>Viscosity</td>
<td>1.85E-05</td>
<td>[kg/ms]</td>
</tr>
</tbody>
</table>
Phase 1: Summary

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Step 1: Open Project Template

a. Click on the Open Project icon.
b. Select the file Fuel Distribution – Phase 1 start.proj in the Case Study 11 Networks directory.
c. Click Open.
d. Select Save Project as… in the File Menu.
e. Save the project as Fuel Distribution - Phase 1.proj.
Step 2: Verify the working fluid

a. In the Libraries window select the Charts and lookup tables Tab and Browse to the Problem specification Fluid, Double click on the Fluid to open the Fluid Dialog.

b. Ensure that the working fluid is defined as shown.
Step 3: Airline Ramp Outlet Pressure

a. Select the Zoom icon.
b. Zoom to the Airline Ramp as seen on the canvas.
c. Multi-select the Boundary Conditions as shown.
d. Enter 345 kPa for Pressure.
Step 4: Select and copy pump element

a. Select **Zoom to Page** to view the entire network.
b. Copy the Fuel Depot Pump.
c. Paste the pump next to the Airline ramp control valve.
d. Zoom to the Airline pump control valve as shown.
e. Replace the Control Valve with Loss Coefficient with the pasted Pump.
f. Change the Pump Description to **Airline ramp booster pump**.
a. Select the **Designer Setup Dialog** icon.
b. Add a new designer Set and rename it to **Booster Pump Speed**.
c. Right-click in the Equality Constraints pane and select add from the context menu.
d. Select the added Equality constraint and specify the component and property by selecting the browse icon in the Component and property column.
Step 6: Create Designer Set for booster pump speed

- Select the **Airline ramp inlet Pipe (E – 18)** from the Components pane.
- Select **Total mass flow** as the property.
Step 7: Create Designer Set for booster pump speed

a. Enter a **Target Value** of 240 kg/s.

b. Add a component in the Independent Variables pane. Similarly as in Step 7, select the Airline ramp booster pump and **Speed** as the variable.

c. Enter a **minimum** of 1 rpm.

d. Enter a **maximum** of 3000 rpm.

e. Right-click on Booster Pump Speed in the Designer Configurations pane and select **Set As Active** from the context list.

f. Close the Designer Set window.
Step 8: Edit cargo ramp control valve and run the designer

a. Select the Cargo ramp control valve.

b. According to the manufacturer, there are some cavitation problems when the control valve fitted in the Cargo ramp fuel line is opened fully. Their recommendation is to operate the valve between 20% and 90% open at all times. Change the Fraction open to 0.9 to run the Designer for the booster pump under these maximum load conditions.

c. Select Designer from the drop down list box.

d. Save the Project.
Step 9: Snap the Project

a. To ensure all the inputs are saved before running the designer, snap the project, open the snap window from the views menu (F8).

b. Select the New Snap icon in the snaps window.

c. Save the snap as MyDesignerStart.snap.

d. Notice the Snap is saved and displayed in the snaps window.

e. The snap is also automatically saved when the designer is run, it is only shown in the tutorial to illustrate how to save a snap at any point in the project.
Step 10: Run the designer & view results.

a. Run the designer to generate the designer results.

b. Notice the Snap DesignerStart is automatically generated.

c. In the Tasks output window, select the Console tab to see the designer progress.

d. Select the airline booster pump to view speed calculated by the designer.
Step 11 Activate mass flow result layer & Solve network

a. Double click on the result layers icon in the tasks tab in the libraries window.
b. Check the Mass Flow rate Result layer to activate it.
c. Set the solver to Default Solver and Solve the network in steady state to view the results.
Step 12: Inspect mass flows in the network & change units

- Select the **Cargo ramp control valve** and select **Results** tab.

- Note that the mass flow rate in the cargo ramp has dropped below the specified rate of **90 kg/s**.

- With the control valve fully opened, it indicates that a single pump running at full speed in the pump house is not enough to supply the new pressurised system and maintain the cargo ramp’s required fuel rate.

- Select **lbm/s** from the drop down list box for Total mass flow.

- Select **psi** from the drop down list box for Mean temperature.

- Note that other units can be selected from the drop down list box.
With the increase in recreational air traffic due to tourism, it was decided to develop the airfield even further into a regional hub airfield handling a larger number of light airplanes in conjunction with the domestic airliners and the cargo depot.

Your tasks are:

- Inspect the company intern’s design of the expanded fuel network in Flownex and check that all outlet valves are fully opened.
- Results from the previous phase indicated that the single pump in the fuel farm was not sufficient to supply the pressurized system at the required mass flow rate. Increase the number of pumps to three in the fuel farm and use an equation element to control their operation based on the pressure of fuel in the main supply line running from the pump house to ensure that overpressure does not occur if all the downstream valves are closed.
- Use the Designer to re-configure the booster pump to maintain 240 kg/s to the airline ramp and to re-configure the cargo ramp control valve in the expanded fuel network to maintain a mass flow of 90 kg/s to the ramp.
Phase 2: Summary

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Step 19: Confirm Designer values and inspect pressures
Step 1: Open the starting network for Phase 2

- Open a instance of Flownex if not already running.
- Select the Open icon.
- Select the file Fuel Distribution – Phase 2 start.proj in the Case Study 11 directory.
- Select Open.
- Save the project as Fuel Distribution – Phase 2.proj
Step 2: Inspect the network

- Zoom to the light aircraft ramp.
- While holding the Ctrl-key select all six control valves.
- Open the properties window to view the inputs of the multi selection.
- Ensure that the Fraction open for all six valves in the Light aircraft ramp is set to 1.0.
Step 3: Adding a script

- In the Libraries Window select the Components Tab expand the Scripting tree and select Script.
- Drag and place the script on the canvas as shown.
- Double-click on the Script to open the Script Component window.
Step 4: How does a Script Component work?

- **a.** A **ScriptComponent** contains a small user-defined **software program** (script) that performs calculations using any properties defined in the network.

- **b.** The equation element monitors the **Input Variables** and uses their values in the script.

- **c.** After the script is executed and all calculations have been completed, the results are sent to the **Output Variables** which return the new values to the elements in the network.

- **d.** By using **Compile and check for errors**, the script is checked for syntax errors, so that errors in the code can be corrected without running the complete simulation.

- **e.** The bottom pane displays any error messages from the script evaluation.
Step 5: Defining the inputs and outputs

```csharp
//script using directives
//css_ref IPS.Core.dll;
//css_ref IPS.PluginInterface.dll;
using System;
using IPS.Properties;
using IPS.Scripting;

//script must be derived from IComponentScript
public class Script : IPS.Scripting.IComponentScript
{
  IPS.Properties.Double m_PSystem;
  IPS.Properties.Double m_DetectSpeed2;
  IPS.Properties.Double m_DetectSpeed3;
  IPS.Properties.Double m_SpeedPump2;
  IPS.Properties.Double m_SpeedPump3;

  double dSpeedOn;
  double dSpeedOff;

  double dHigh;// The high pressure mark
  double dLow;// The low pressure mark

  //do pre simulation initialization here
  public override void Initialise()
  {
  }

  //do post simulation cleanup here
}
```

a. In the script box enter the following in lines 11 to 13 to specify the inputs that will be used.

b. Define the outputs as shown in line 15 and 16.

c. **PSystem** represents the main fuel pipe, and **DetectSpeed2 and 3 and SpeedPump 2 and 3** represents Pump 2 and 3 respectively.

d. Specify speed and pressures values as doubles as shown in lines 19 to 23.

The script defines high and low cutoff pressures for the pumps and tests the pressure in the main fuel line (defined as **PSystem**) to determine if it should increase or decrease the fuel rate by controlling the number of pumps switched on.

If the pressure drops below the **dLow** value, the pumps are switched on in sequence.

Pump 3 is only switched on when the pressure is still too low and Pump 2 is already running.

When the pressure rises above the **dHigh** cutoff value, the pumps are switched off to reduce the mass flow in the main supply line (Pump 3 is switched off first).
Step 6: Script the main execution function

```java
public override void Execute(double Time)
{
    // calculates the base 10 logarithm of the input
    if (m_PSystem.Value <= dLow)
    {
        m_SpeedPump2.Value = dSpeedON;
    }
    else if (dHigh <= PSystem.Value && DetectSpeed3.Value < 3000)
    {
        m_SpeedPump2.Value = dSpeedOFF;
    }
    else if (dLow < PSystem.Value && dHigh > PSystem.Value && DetectSpeed2.Value > 1)
    {
        m_SpeedPump2.Value = dSpeedON;
    }
    else
    {
        m_SpeedPump2.Value = dSpeedOFF;
    }

    if (dLow >= PSystem.Value && DetectSpeed2.Value > 1)
    {
        m_SpeedPump3.Value = dSpeedON;
    }
    else if (dHigh <= PSystem.Value && DetectSpeed3.Value < 3000)
    {
        m_SpeedPump3.Value = dSpeedOFF;
    }
    else if (dLow < PSystem.Value) && (dHigh > PSystem.Value) && (DetectSpeed3.Value > 0)
    {
        m_SpeedPump3.Value = dSpeedON;
    }
    else
    {
        m_SpeedPump3.Value = dSpeedOFF;
    }

    // constructor initialises parameters
    public Script() {
        m_PSystem = new IPS.Properties.Double();
    }
```
Step 7: Construct the parameters

a. Define new doubles as shown from line 78 to 86.

```java
// constructor initialises parameters
public Script()
{
    m_PSystem = new IPS.Properties.Double();
    m_DetectSpeed2 = new IPS.Properties.Double();
    m_DetectSpeed3 = new IPS.Properties.Double();
    m_SpeedPump2 = new IPS.Properties.Double();
    m_SpeedPump3 = new IPS.Properties.Double();
    dSpeedON = 3000;
    dSpeedOFF = 1;
    dHigh = 1200; // The high pressure mark
    dLow = 730; // The low pressure mark
}
```
Step 8: Enter the return scripting

```java
// property declarations to make
// parameters visible to outside world

public IPS.Properties.Double ESYS
  get
  { return m_ESYS; }

public IPS.Properties.Double DetectSpeed2
  get
  { return m_DetectSpeed2; }

public IPS.Properties.Double SpeedPump2
  get
  { return m_SpeedPump2; }

public IPS.Properties.Double SpeedPump3
  get
  { return m_SpeedPump3; }

public IPS.Properties.Double DetectSpeed3
  get
  { return m_DetectSpeed3; }
```

a. Enter the `return` scripting as shown in line 93 to 136.
Step 9: Execute the script

a. Press the **Compile and check for errors** button. Ensure that **SUCCESS** appears in the bottom pane.

b. Press **Execute and test script**.

c. Notice the defined variables are displayed under the Script inputs and outputs.
Step 10: Inserting the Script component input links

- a. Select the **Data Transfer Tool** icon.
- b. First left-click on the **pipe** and then on the **script component** (the arrow of the link indicates the direction of communication)
- c. Automatically the Setup Data Transfer Link Dialog will Appear. To Link the **Mean pressure** of the pipe to the script component drag it over to **PSystem** on the scrip side. This will link the properties.
- d. Press **OK**.
Step 11: Inserting the Script component input links (2)

a. Insert a data transfer link from supply 2 to the script component.

b. Automatically the Setup Data Transfer Link Dialog will appear. Link Speed from supply pump 2 and drag it over to Detect Speed 2 on the script side. This will link the properties.

c. Similarly drag and drop Speed on DetectSpeed3, after completing a data transfer link between supply pump 3 and the script component.

Hint: Outputs are linked in the same manner, but with the link going in the opposite direction. (By first clicking on the Script Component and then on the other element).
Step 12: Inserting the Script component output links

a. Similarly insert **data transfers** from the script component to supply pump 2 and 3.

b. Drag and drop **SpeedPump2 and 3** on Speed for both links.
Step 13: Open the control valve for booster pump design

a. Select the Cargo ramp control valve.

b. Change the Fraction open to 0.9 for full flow conditions.
Step 14: Re-configure booster pump speed

a. Open the Designer Configuration window by selecting the Designer icon.
b. Ensure the Mass flow and Speed variables are setup correctly.
c. Activate Booster pump speed.
d. Save the project, change the solver to Designer and Run to activate the Designer solution process.
e. Ensure designer has found a solution.
To obtain the required mass flow of 240 kg/s the Airline ramp booster pump must run at the speed of 1720 rpm in the expanded network.
a. Select the Cargo ramp control valve.

b. Change the Fraction open to 0.2 to start the Designer with minimum flow conditions. This helps the convergence algorithm of the Designer to approach the optimizing problem from the correct direction and reduces the probability of a diverging design solution.

(Note: The control valve must be throttled back from the fully open position to reduce the mass flow to the specified value of 90 kg/s.)
a. In the initial system, the mass flow to the cargo ramp was too low and thus below specification. With the extra pumps increasing the mass flow, the cargo ramp control valve for the new system must now be closed to reduce the mass flow to meet the original specification. Do this by adding Activating the Calc Valve fraction open Designer Set in Designer Configurations pane.

b. Ensure the Equality Constraint and independent variables are specified correctly.

c. Solve the Designer.
Step 18: Inspect the Designer values

- Select the Cargo ramp control valve.
- To obtain the required mass flow of 90 kg/s the valve must open at a fraction of 0.45 in the expanded network.
Step 19: Confirm Designer values and inspect pressures

a. Activate the Pressure result layer.
b. Set the solver to default Solver save the project and solve.
c. When the solver has converged, the results layer will automatically update to show the most recent pressure values.
d. (Hint: The maximum and minimum values of the colour scale can be adjusted in Edit Result Layer to focus in on a certain range of values in the results or select ADL for auto detect limit.)
Phase 3: Emergency valve shutdown

The valves used on the refueling hoses are normally closed valves (that is, in the event of any failure in the system, the valves are automatically closed for safety reasons). Investigate the effects of a power failure on the fuel system in terms of water hammer when the valves are suddenly closed.

**Your tasks are:**

- Insert transient sets to simulate a power failure and sudden valve closure in the light aircraft and airline ramps. Assume the refueling systems at all ramps were in full operational status at the time.

- Insert a graph component and gauge displays to monitor the pressure surge and pump speed in relevant elements in the network.

- Investigate the effect of the pipe discretization (number of pipe increments) on the prediction of the water hammer effect. Compare the maximum pressure in the outlet valve pipes and the general pressure behaviour of the starting network with a network which uses multiple increments in the pipe elements.
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Step 1: Open starting network for Phase 3

a. Open a instance of Flownex if not already running.
b. Select the Open icon.
c. Select the file Fuel Distribution – Phase 3 start.proj in the Case Study 11 directory.
d. Select Open.
e. Save the project as Fuel Distribution Phase 3.proj
Step 2: Edit the scheduler

a. Open the scheduler window by selecting the Tasks tab in the libraries window and double-clicking on Scheduler.
b. Change the Time Step Size to 0.1 s.
c. Change the End time to 10 s.
Step 3: Create a scenario

a. Open the Actions Dialog by selecting the Tasks tab in the libraries window and double-clicking on **Actions**.

b. Add a Scenario by selecting New Scenario in the context menu after right clicking in the scenario pane and rename it to **Transient Set 1/Emergency valve closure**.

c. Select the browse icon in the **Trigger** column to open the **Trigger Type Dialog**, set the **Start Time** to 0 s and the **Duration** to 10 s.
Step 4: Create the individual action for the valve scheduler

a. Add a **New Action** and rename it **Scheduler Valve**.

b. Select the browse icon in the **Trigger** column to open the Trigger Type Dialog, set the **Start Time** to 0 s.

c. Select the browse icon in the Target column to open the Specific property selection dialog. Under the Tasks column select the **scheduler** as the **Element** and **Time step size** as the **property**.

d. Set the **Value Type** to constant and the **Value** to 0.01 s.
Step 5: Create the individual actions for the valves

- Add a action for the first valve and name it **Valve 1_1**.
- In the **Trigger** column set the **Start Time** to **0 s**.
- Select the Control Valve with Loss Coefficient, **E – 20**, and **Fraction Open** as the variable.
- Select **LINE** under Value Type and set the Value to **-10, 1**.
- Set the minimum value to **0**.
Step 6: Create the individual actions for the valves

- Similarly create Actions for Valve 1_2 to Valve 1_6 and rename the Actions accordingly, the Targets, Value Type and values can be seen in the Actions Task Dialog above.
- Continue further and repeat the steps for the two valves in the airline ramp as well: Valve 3_1 and Valve 3_3.
a. When the valves for the pressurized ramp are closed, the booster pump must also be switched off using a gradual function to limit surge in the network. Add a new Action, Booster Pump Shutdown.

b. Select the component Variable Speed Pump, E – 3 and Speed.

c. Specify the pump shutdown event by specifying the event equation as $1682 - 1681t$ by entering the coefficients into the equation editor. (This means that the pump starts at its operating speed of 1682 rpm and in a second ramps down to 1 rpm).

d. Under Trigger set the Start Time to 0.001 s and the Duration to 0.01 s.

e. Add a Scheduler Shutdown and change the scheduler time step size to 0.1.

f. Add a action Booster Pump Idle and select E – 3 and Speed. The pump should idle at a constant speed of 1 rpm without any time dependence, so enter a constant value of 1 in the coefficients.

g. Under Trigger, set the Start time to 1.001 for the Scheduler and the Booster Pump Idle.
Step 8: Snap the Project

a. Press F8 to view the snaps window.

b. Select the New snap icon to save a new snap and save it as Start.snap.
Step 9: Create a Graph on the canvas

a. Select the **Line Graph** and drag and drop it on the canvas.

b. Use the **Select** tool to move and resize the line graph to a convenient location.

c. Select the **Main fuel pipe** and select the **Results** tab.

d. Select **Mean Pressure** and drag and drop it on the graph.
Step 10: Using a graph component (2)

a. Select the graph and press F4 view its properties.
b. Select Yes under Auto-scale axis (X-Axis)
c. Select No under Display multiple Y-Values.
d. Select No under Auto-scaling (Y-Axis)
e. Change the Maximum value to 1700.
f. Change the Minimum value to 700.

(Now the graph component will display the real-time pressure level in the main fuel line).
Step 11: Use a dial component to display pump speed

a. Select the **Dial Component** and drag and drop it on the canvas.

b. Edit it as shown, similar to **Tutorial 5**.

c. Select the dial and edit its properties, Select the **Browse** icon on the **Property** input to open the property selection dialog and select **Supply pump 1, E – 1**, and **Speed** as the variable.

d. Change the **Maximum** value to 3000 and the **Minimum** to 0 (so that the dial on the gauge will match the maximum speed rating of the pump it represents).
a. Repeat the steps from the previous slide to insert speed dials for the other two supply pumps: Supply pump 2 and Supply pump 3.

b. Also insert a speed dial for the Airline ramp booster pump and set the Maximum to 3000 rpm.

c. (Hint: By right-clicking on a component and using Copy-and-Paste and changing the Selected Entity of the new dial to match the new element, additional dials for other components can quickly be added to the canvas).
Step 13: Solve and inspect pressure distribution in the network

a. Activate the **Pressure Result Layer** for all the components as shown.

b. **Solve Steady State**.
Step 14: The pressure distribution in the network

- Load the **Start snap, Solve Steady State** and **Run** the transient solution.
- Notice the **gauges** that indicate the pump speed. The **second** and **third** supply pumps have been shutdown due to rising pressure from the water hammer in the system.
- The **Graph Component** shows the value of the pressure in the main fuel line as time progresses.
- Notice the build-up of pressure due to water hammer.
- The **Pressure Parametric Layer** gives a visual indication of the pressure distribution inside the network.
- Notice the fluctuations in pressure due to the emergency valve closure.
- The **colour scale** depicts the scale used for the colour of the pressure values in elements.
Step 15: The mass flow rates in the network

- a. Activate the **Mass flow rate Parametric Layer** and run the **solver** again to view the transient behaviour of mass flows in the different elements. *(In the same manner as shown in a previous slide for the Pressure Results Layer).*

- b. The Results layer now gives a **visual** indication of the **Mass flow rate** and the scale with which it varies, where **red** represents **higher** rates and **blue** represents the **lower** rates.

- c. Notice that the **Airline ramp booster pump** is gradually **ramping down** its speed due to the power failure.

- d. The graph component still shows the **pressure** in the **Main fuel line**, because it is configured **separately** from the Results Layer.
Step 16: The water hammer graph set

- Select the Graphs tab in the Project explorer window.
- Expand the Water hammer Folder to view the graphs defined in the Graph Set.
- Open the graphs with a double right click.
- Notice the Pressure profiles plotted for the Main fuel pipe and for one of the pipes in the ramp distribution section.
- The second graph shows the Speeds for the different pumps in the system.
- The booster pump gradually shuts down.
- The grey top shows Supply pump 1 operating continuously.
- Supply pumps 2 and 3 switch on and off following the pressure wave in the network.
Step 17: The control valve pipes graph set

- Click on the Control valves pipes tab to view the graphs defined in the Graph Set.

- Notice the Pressure profiles in all of the inlet pipes to the control valves. The pressure waves due to the emergency valve shutdown can clearly be seen.

- Inspect the maximum values of the pressure waves in the high-pressure outlet pipes.

- The graph legends can be user-defined in the Graph Set for easier readability.
Step 18: Increase the number of increments in all pipes

- Load **start** snap.
- Click on **Find** icon to open the find dialog to search for pipe elements.
- Click on **Type** and choose **Pipe** from the list.
- Expand All
- Left-click on the **first** pipe in the list.
- Press and HOLD the **SHIFT** key and select the **last** pipe in the list.
- Notice that all the entries are **highlighted** and that all the pipe elements on the canvas are selected.
- Click **Close**.
- Change the **Number of increments** to **20**. This will change the same property for all selected pipes.
- Click on **File**>**Save Project As** to save the project with the new name of **Fuel Distribution – Phase 3 – 20 increments.fnz**
- The inputs can also be saved as a snap - **20 increments.snap**
- Press **Solve** to solve the new network.
Step 19: Evaluate the improved results

- Click on the Control valve pipes pressure graph to inspect the pressure waves in the control valves.
- Compare the general profile to the pressure plot from the previous steps and investigate the changes in the solution.
- The new maximum value is shown as 3500 kPa, which is a change of about 1.5%.
- Despite the small change in maximum value, the general pressure behavior predicted with the new network is quite different from the one-increment-per pipe-network, which shows that the pressure waves are captured better by using more increments in the pipes.
You have successfully completed this tutorial!