# Capacity building on designing and manufacturing shell-and-tube heat exchangers

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*This document describes the activities aiming to build capacity, on equipment manufacturers in Ghana, to design and construct shell-and-tube-heat exchangers. As part of the training, a unit was built and installed at a processing centre that uses a pneumatic dryer to produce cassava flour. The results of a preliminary study, comparing the newly build shell-and-tube heat exchanger against a double-pipe one is also presented. The activities were funded by the CGIAR Research Program on Roots, Tubers and Bananas (RTB) and executed by the Natural Resources Institute (NRI) of the University of Greenwich, UK, in partnership with the Food Research Institute (FRI) of the Council for Scientific and Industrial Research (CSIR), Ghana.*

## Background

Heat exchangers are devices that transfer heat between two fluids, where each fluid is separated by a solid wall to prevent mixing. In the context of convective drying, heat exchangers are used to transferring the heat from the burner's combustion gases to the drying air. Several types of heat exchangers are used in food processing, but the most common types are the double-pipe and the shell-and-tube.

In the majority of cassava processing centres in sub-Saharan Africa, locally manufactured dryers are fitted with a double-pipe heat exchanger (Figure 1). This type of heat exchanger is simple to build and maintain but has limited heat transfer surface – the area between the two fluids. Heat exchangers efficiency depends largely on the extent of the heat transfer surface, and consequently, the energy efficiency of this kind of heat exchangers is inheritably low.

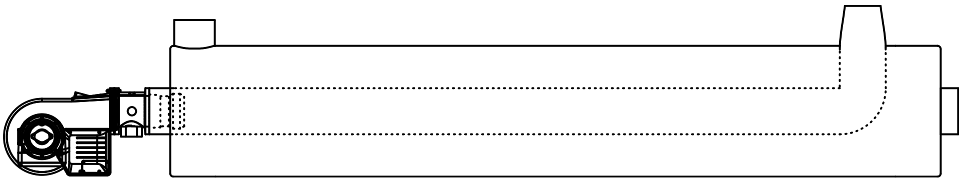

**Figure 1** Double-pipe heat exchangers are the simplest type and consist of two concentric pipes.

Shell-and-tube heat exchangers, on the other hand, have much larger heat transfer surface and consequently higher efficiency. Shell-and-tube heat exchangers contain a bundle of parallel tubes enclosed in a shell (Figure 2). Inside the shell, there are also baffles and expansion joints. Baffles are for guiding the fluid and ensure if flows in the correct pathway, but they are also used to support the tubes. Expansion joints are for relieving the pressure built from the thermal expansion.

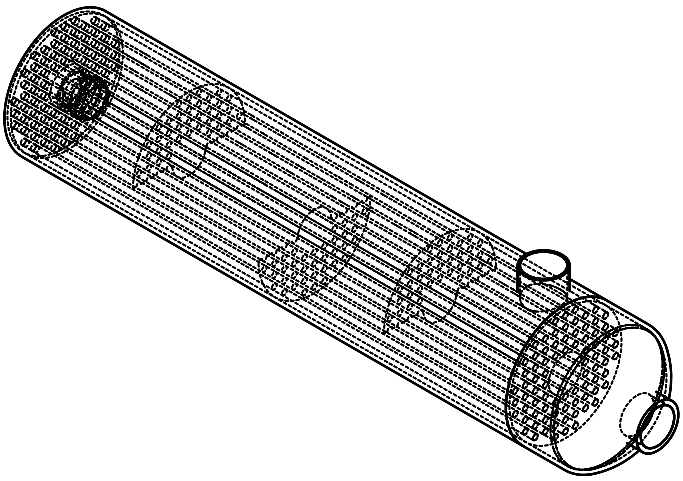

**Figure 2** Shel-and-tube heat exchangers contain a bundle of parallel tubes enclosed in a shell.

The design and construction of shell-and-tube heat exchangers are more complex than of the double-pipe one, therefore, the objective of this task was to develop capacity on equipment manufacturer in Ghana in designing and manufacturing shell-and-tube heat exchangers. As part of the training, a heat exchanger was built, fitted to a pneumatic dryer, and evaluated.

## Provisional double-pipe heat exchanger

In 2018, as part of RTB activity, equipment manufacturers in Ghana learned how to dimension and build pneumatic dryers for cassava processing (Figure 3a). During the training, a pneumatic dryer was manufactured and installed at a cassava processing centre named Tropical Starch (Figure 3b). Provisionally, a double-pipe heat exchanger was installed to the dryer (Figure 4a), while awaiting the construction of the shell-and-tube heat exchanger. A diesel burner model B26, manufacture by Bairan, was used to generate the heat (Figure 4b). This burner had a power output ranging from 118 kW to 308 kW.

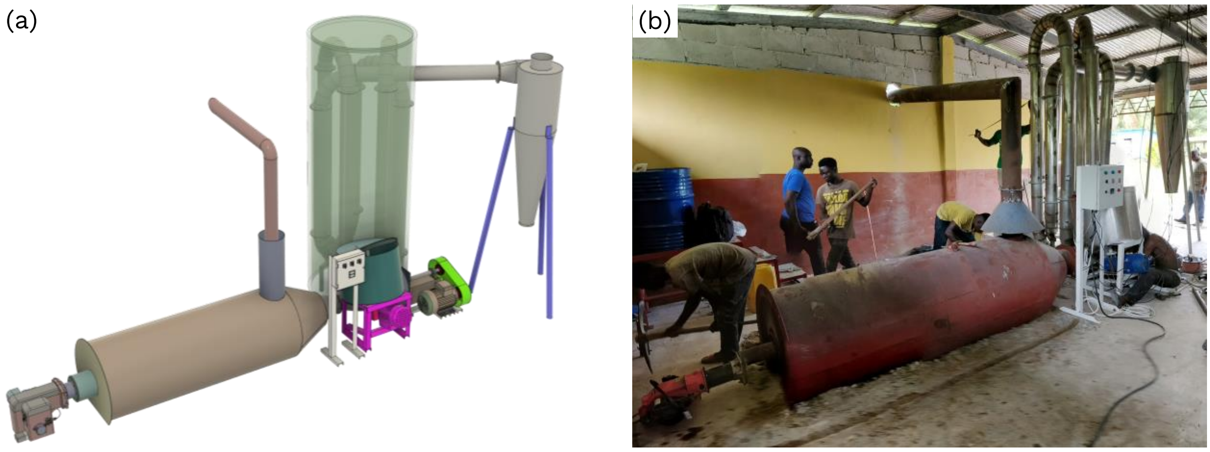


**Figure 3** Pneumatic dryer designed (a) and built (b) during capacity building activities with equipment manufacturer.

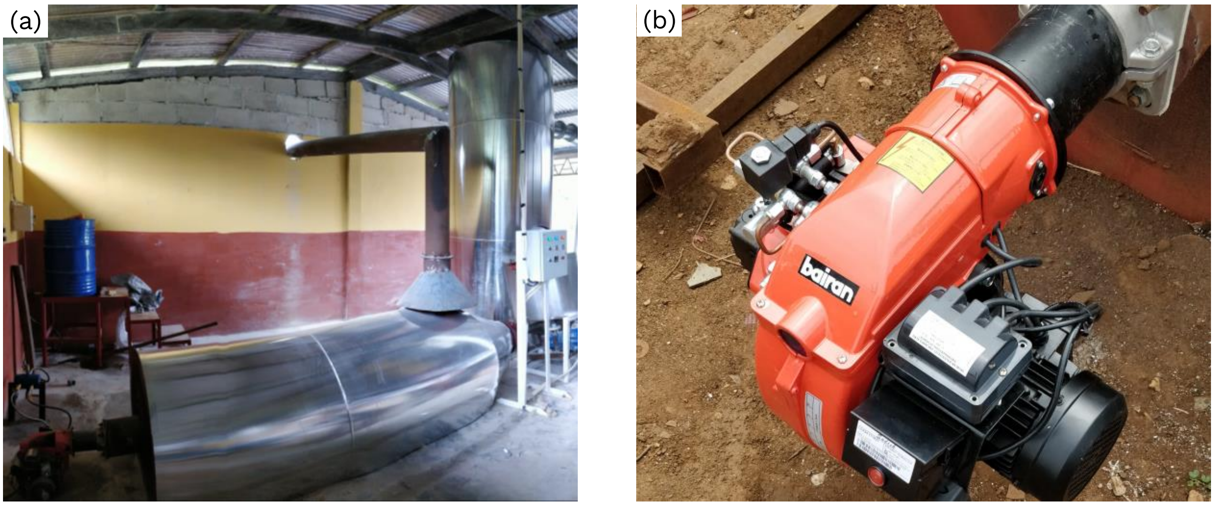


**Figure 4** Double-pipe heat exchanger (a) and Bairan diesel burner (b), provisionally fitted to the pneumatic dryer.

## Shell-and-tube heat exchanger

The shell-and-tube heat exchanger that replaced the double-pipe one at Tropical Starch was dimensioned and designed by Dr Arnaud Chapuis, a researcher in Food Process Engineering at CIRAD, France. The unit was composed of two blocks, assembled one on top of the other. At the bottom was the combustion chamber and at the top the tube bundle (Figure 5). To increase the heat and transfer surface, turbulators were inserted into each of the tubes (Figure 6).

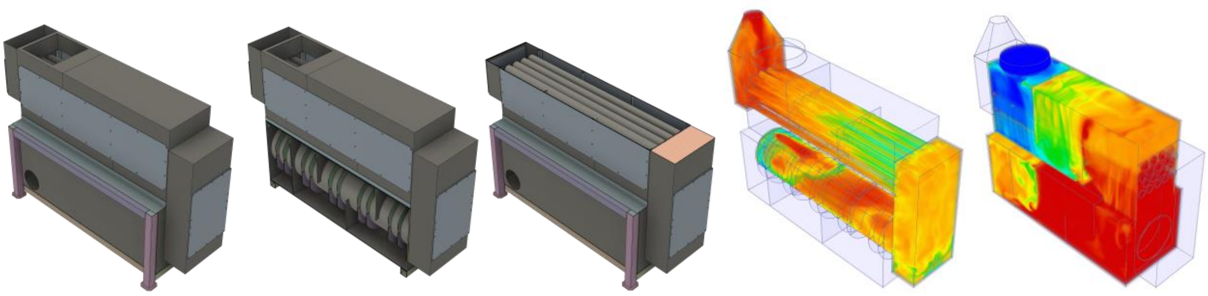

**Figure 5** Shell-and-tube heat exchanger with a combustion chamber at the bottom and tube bundle at the top.

**Figure 6** Turbulators were designed to be inserted into each of the heat exchanger's tube to increase heat transfer.

The heat exchanger was built and fitted to the dryer at Tropical Starch (Figure 7), replacing the double-pipe heat exchanger. Additionally, the Bairan diesel burner model B26 was exchanged by the model B10 that had a smaller power output, ranging from 59 kW to 118 kW.

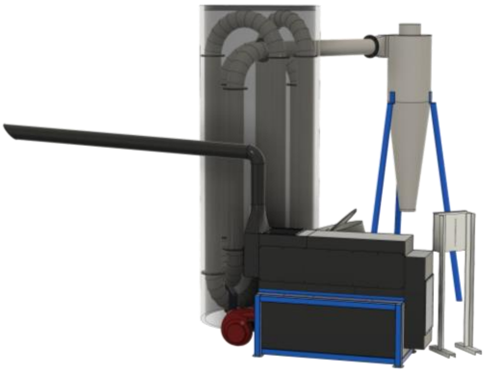

**Figure 7** Shell-and-tube heat exchanger replaced the double-pipe heat exchanger at Tropical Starch.

Afterwards, the equipment manufacturers learned how to use the *Heat Exchanger Design Tool*, an Excel-based software developed by Arnaud Chapuis to dimension heat exchangers (Figure 8).

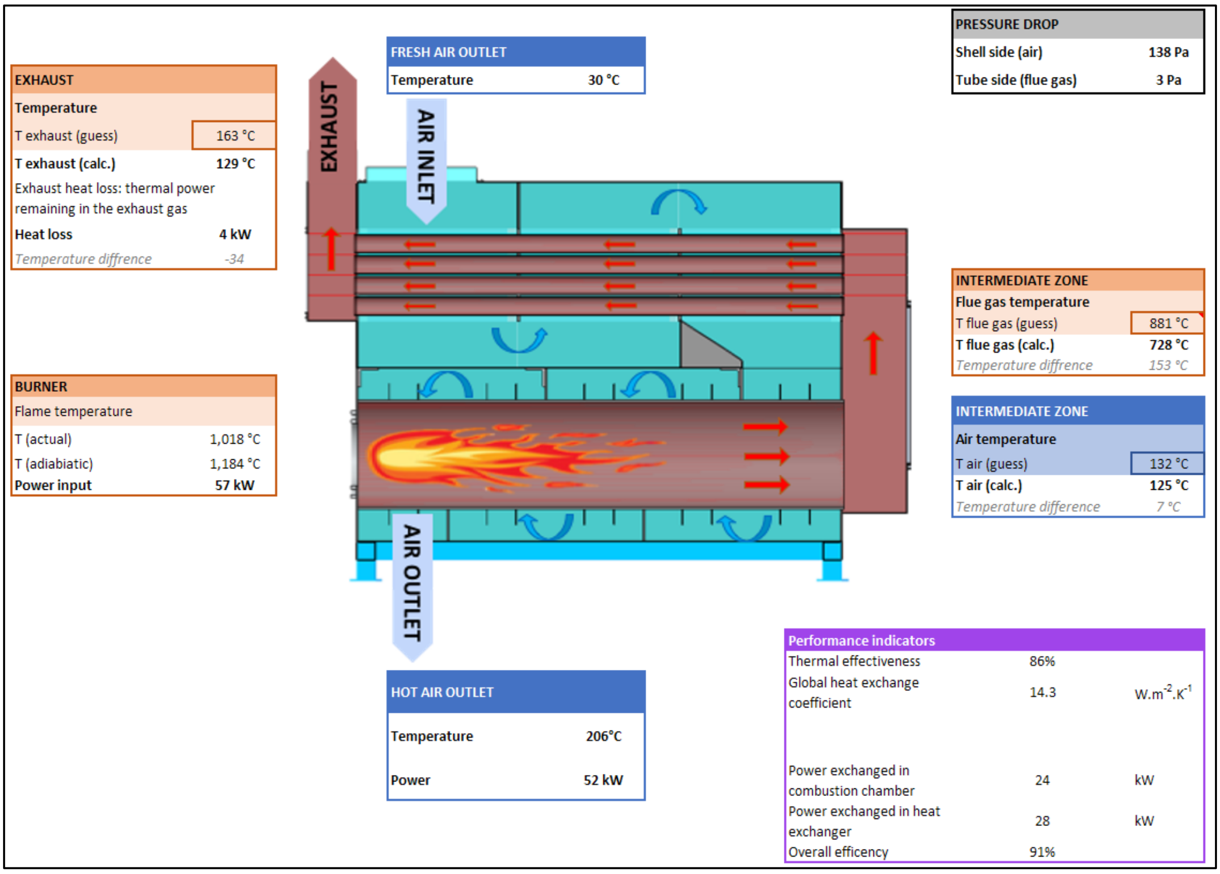


**Figure 8** Screenshot of the *Heat Exchanger Design Tool*, a software developed by Dr Arnaud Chapuis from CIRAD.

## Heat exchanger energy performance assessment

The capacity building activities also included evaluating the energy performance of the equipment built and comparing it with the provisionally double-pipe one. In general, for evaluating heat exchangers performance, the main indices are *Overall Heat Transfer Coefficient*, *Fouling Factor*, *Log Mean Temperature Difference*, *Effectiveness Number of Transfer Units* and, *Overall Efficiency*. However, to make easier for the learners, only *overall efficiency* ($\eta_{hx}$) was used. It was defined as the ratio between the heating duty ($\dot{Q}_{hx}$) and the heat input from the diesel ($\dot{Q}_{diesel}$), as shown in Equation 1:

$$\eta_{hx} = \frac{\dot{Q}_{hx}}{\dot{Q}_{diesel}} = \frac{\dot{m}_{air} \bullet (h_{out} - h_{in})}{\dot{m}_{diesel} \bullet H_{diesel}} \quad (1)$$

Heating duty was calculated multiplying air mass flow rate ($\dot{m}_{air}$) to the difference between the air enthalpy from the air entering the heat exchanger ($h_{in}$) and the enthalpy from the air leaving the heat exchanger ($h_{out}$). The difference in enthalpy was used instead of the difference in temperature to allow accounting for the influence of the high relative humidity of the ambient air. Heat input from the diesel was calculate multiplying the fuel mass flow rate ($\dot{m}_{diesel}$) by its heating value ($H_{diesel}$), entered as 42.5 MJ/kg.

Air mass flow rate was obtained from the air volume flow and its density. Air volume flow was calculated multiplying air velocity to the cross-sectional area of the last part of the drying duct, where the air velocity measurement was performed (Figure 9). This measurement was made with no material being fed to the equipment and at ambient temperature, with the diesel burner off. During air velocity measurements, values of temperature, relative humidity and pressure were also recorded and used to calculate the air density.

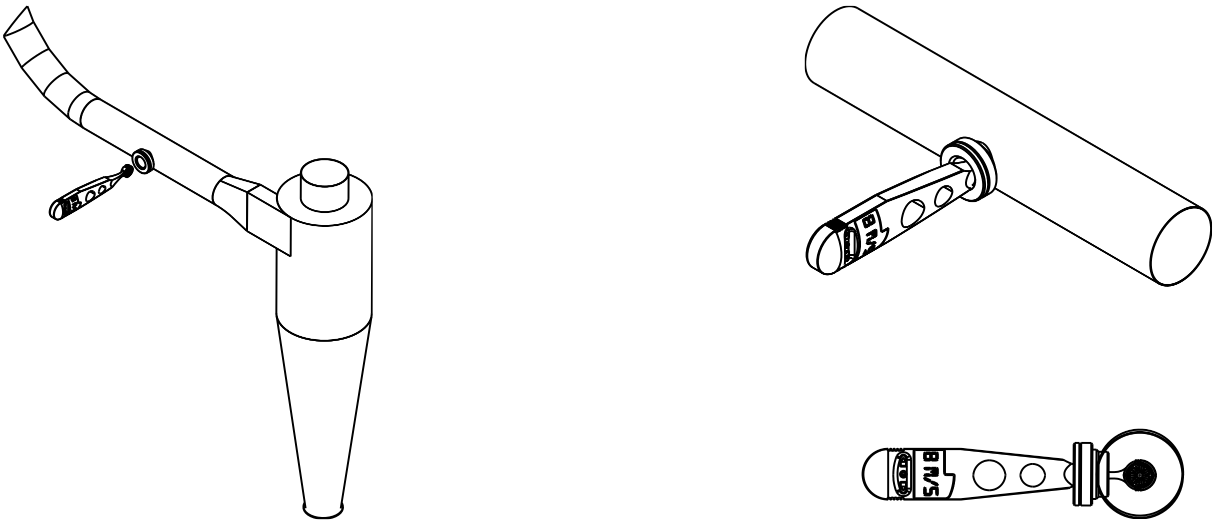

**Figure 9** Air velocity was measured at the end of the dryer's drying duct, with the diesel burner off.

Enthalpy from the air entering the heat exchanger was obtained from the ambient air temperature, relative humidity and pressure, recorded at every minute during the trials. Enthalpy from the air leaving the heat exchanger was obtained from the temperature, relative humidity and pressure of the heat exchanger outlet, just before the feeder, as shown in Figure 10.

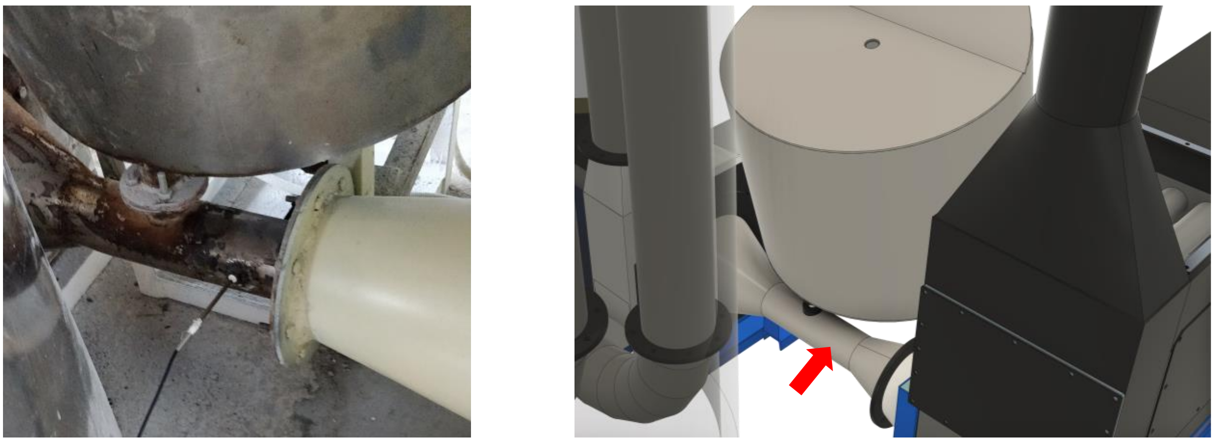

**Figure 10** Location where the temperature of the air leaving the heat exchanger was recorded.

During trials, air temperature at the heat exchanger outlet ($T_{out}$) was recorded at every minute. Air relative humidity was calculated from the ambient air absolute humidity, and the pressure was calculated from the pressure drop, measure with the burner off and no material being fed to the dryer.

The fuel mass flow rate was obtained by placing the fuel tank on a weighing scale and recording every 30 min the reduction on its mass (Figure 11).


**Figure 11** During trials a weighing scale was placed under the fuel tank and the reduction on mass recorded.

Data was collected during the normal operation of the dryer at Tropical Starch processing centre, before and after replacing the double-pipe heat exchanger with the shell-and-tube one. Measurements were made on 5 consecutive days for each heat-exchanger, starting with the, already in place, double-pipe one. On each day, data was recorded over a period of 5 hours and initiated only after the dryer has been in operation for 1 hour, to make sure a steady-state condition has been achieved. Table 1 shows the results of the performance evaluation.

***Table 1*** *Results from the assessment of the double-pipe heat exchanger and the shell-and-tube heat exchanger.*

| **Heat exchanger type** | $T_{in}$ Ambient temperature (°C) | $T_{out}$ Outlet temperature (°C) | $\dot{m}_{diesel}$ Diesel mass flow (kg/h) | $\dot{Q}_{hx}$ Heating duty (kW) | $\eta_{hx}$ Overall efficiency (%) |
|---|---|---|---|---|---|
| **Double-pipe** | 35.0[a] | 231.1[a] | 2.92[a] | 26.0[a] | 75.5[a] |
| **Shell-and-tube** | 28.3[b] | 263.6[b] | 3.34[b] | 34.2[b] | 87.7[b] |

Means followed by a common letter are not significantly different by Fisher's Least Significant Difference (LSD) test at 5% level of significance.

The ambient air temperature was on average lower during the trials evaluating the shell-and-tube heat exchanger. In addition, during the trials evaluating this heat exchanger, the thermostat that controls the diesel burner was adjusted at a higher temperature. This was done because the wet solid being fed to the dryer had a higher moisture content. As a consequence, $T_{out}$ was higher and, accordingly, $\dot{Q}_{hx}$ was also higher. Fuel consumption was greater for this heat exchanger too, however, $\eta_{hx}$ shows that the ratio between heating duty and heat input from the diesel combustion was significantly higher for the shell-and-tube heat exchanger. With 1 kilogram of diesel, the double-pipe heat exchanger was able to produce, on average, 32.1 MJ of heat while the shell-and-tube produced 37.3 MJ, being this difference significant by Fisher's Least Significant Difference test at 5% level. Therefore, if the heating duty would have been the same, fuel consumption while using the shell-and-tube heat exchanger, would have been lower than while using the double-pipe.

## Heat exchanger construction cost

The construction of the shell-and-tube heat exchanger was part of the capacity building activities. This made difficult to determine its actual manufacturing cost. However, considering only the material expenditures, it is estimated that the double-pipe heat exchanger cost approximately USD 1,500 and the shell-and-tube one cost about USD 2,000.