Application Note
New System for Process Control in a Tumble Dryer

1 Current market needs

Currently, two main market trends in the field of tumble dryer consumers can be observed: The desire for an individual way of laundry treatment and the need for optimized energy consumption. Individual laundry treatment – taking care of delicate materials or well tuned levels of residual moisture in the cloths – require diversified programs. A better understood drying process with in-situ measurement of the parameters may allow for an intelligent way of drying, adapting the program to an actual load. With exact, time resolved information about the process the energy consumption may be controlled and improved. Eventually, such information can only be acquired by a new generation of humidity sensor technology – which will be the key for future tumble dryer systems.

2 Drying systems using humidity sensors

Measuring relative humidity and temperature of air after the drum allows for controlling the laundry drying process. The level of relative humidity gives information on the efficiency of the drying processes and when it eventually drops, because the laundry gets dry, the process may be cut off according to an individual criteria.
Figure 2 displays the scheme of a condensation principle tumble dryer consistent of a drum, containing the laundry, the lint filter, eliminating fluff and lint from the air circulation, a sensor to measure humidity and temperature, the condenser, usually passive cooled by the surrounding air, and a heater coil.
Hot, dry air (T_1, RH_1) is blown into the drum. Water from the laundry is evaporating and is absorbed by the air increasing the water content of the air. The hotter the air the higher the water saturation level. After passing the lint filter a packaged sensor measures temperature and humidity (T_2, RH_2) of the moisturized air. In the displayed case the position of the packaged sensor is closer to the condenser as to the lint filter – as long as condensation in the flow channel can be avoided the sensor can be placed anywhere in between of lint filter and condenser.

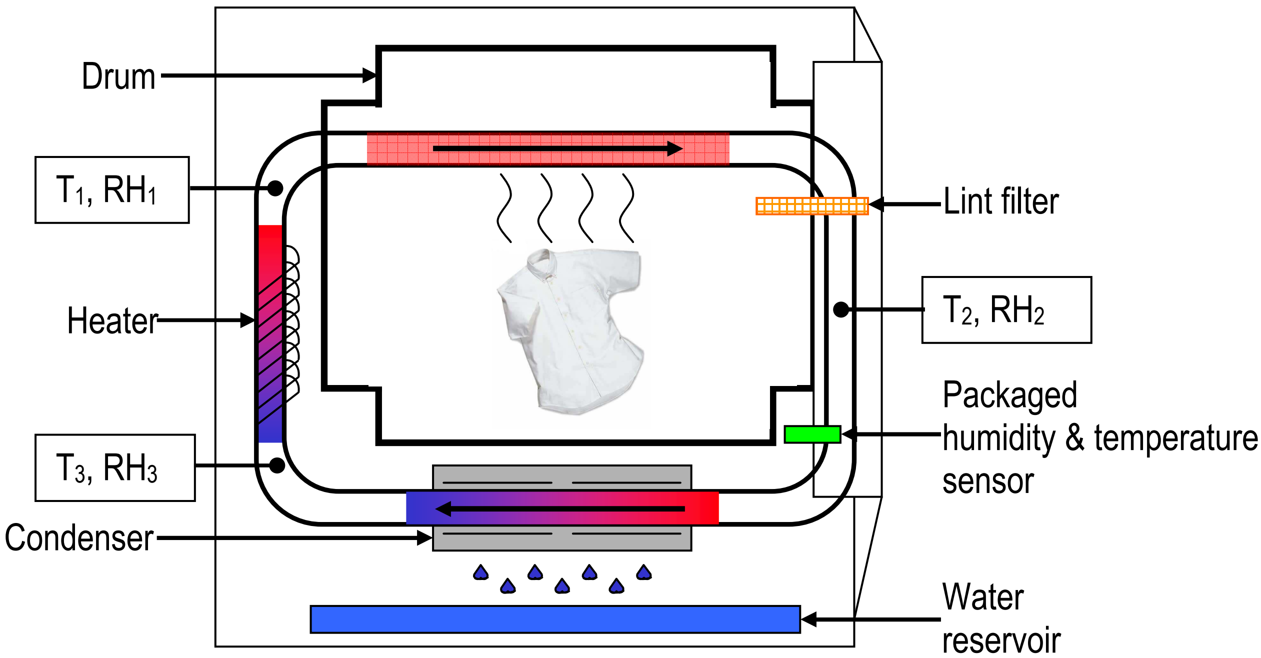

Figure2: Scheme of a tumble dryer based on the condensation principle

The condenser is cooling down the air and the water is condensing - with the lower temperature the capacity for water content of air is reduced. Thereafter, a heater coil is reheating the air (T_1>T_3) lifting the capacity of water absorption before it is brought back to the drum.
As an option for advanced process control, T_1 and RH_1 may be measured by adding another sensor built in the flow channel before the drum. A basic approach, however, is to focus on the measurement of RH_2 and T_2. This information can define the cut-off criteria and termination of the drying process.

3 How to optimize energy consumption

In proposed process control mechanism, temperature and relative humidity (with related dew point temperature and absolute humidity) are the major parameters regulating a tumble dryer process. Figure 3 shows a diagram explaining the different phases of a drying process with related parameters.
Point 1 represents the condition of the heated air before entering the drum. For an advanced drying program – as mentioned before – Point 1 can be determined with the help of an additional sensor placed before the drum. With the knowledge of the condition of the air before and after the drum it is possible to calculate e.g. the evaporation energy and the mass of water withdrawn from the laundry.
The dashed arrow from Point 1 to Point 2 is representing the water absorption of the air in the drum. Water evaporates from the clothes and drives the air close to the saturation point. After the drum humidity and temperature is measured at the sensor position – Point 2. At the condenser - between Point 2 and Point 3 - water condensates from the air while it is cooled. In the diagram the path evolves along the dew point line. Eventually, the heater rises the temperature while the absolute humidity level of the air remains constant, see the path from Point 3 to Point 1. While absolute humidity remains constant - there is no source nor drain of water – the relative humidity is decreasing because the absorption capacity of the air is increased.

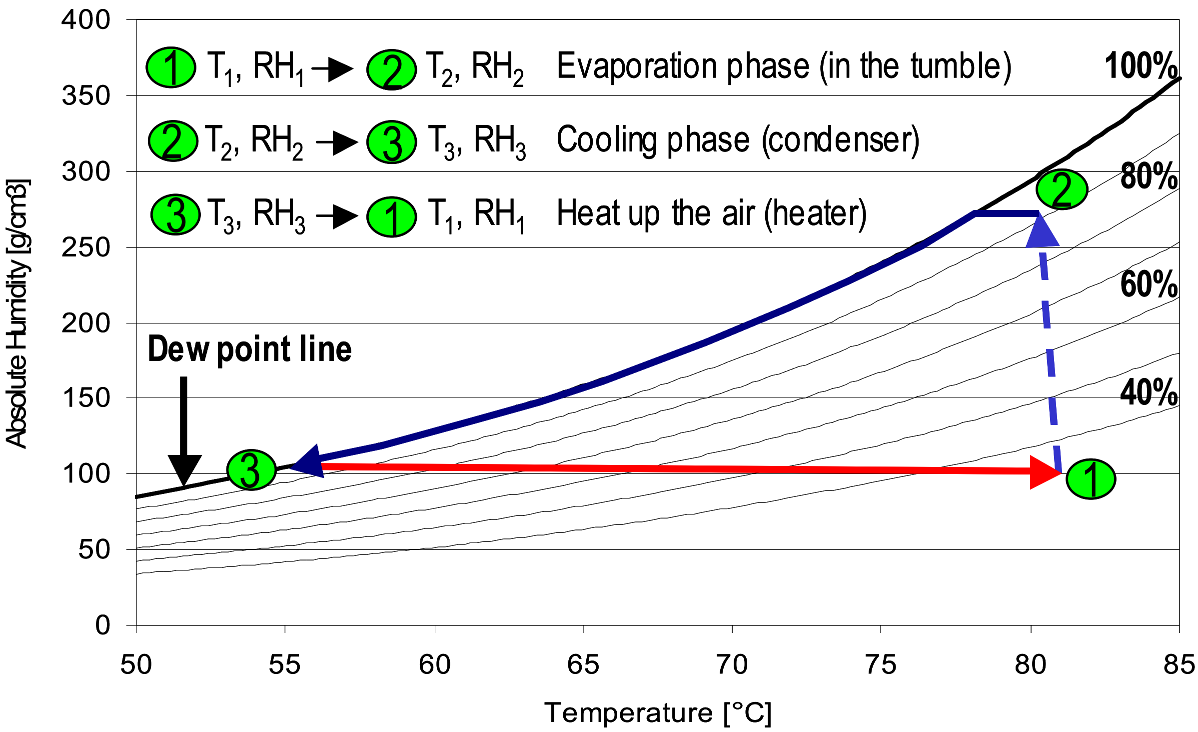

Figure3: Humidity diagram with a typical path of a drying process in a tumble dryer. Relative humidity is given in equivalent lines towards absolute humidity and temperature. The rising dew point line indicates the higher water absorbance capacity of the air at higher temperatures.

Most tumble dryer systems apply passive cooling, thus the air temperature in the system at Point 3 cannot be lower than the ambient temperature outside the system. The relative humidity at this point will be close to 100%. Point 1 then is dependent of the amount of thermal energy fed into the system by the heater – the absolute humidity remains constant but the relative humidity is lowered due to the increased water absorption capacity of the air at higher temperatures. The temperature at Point 2 may be somewhat lower than at Point 1 due to the evaporation which consumes some energy – the relative humidity mainly depends on water evaporation in the drum which is dependent on air flow, size of the drum and eventually on wet state of the laundry. The energy efficiency of the drying process may be engineered by choosing an optimized temperature and humidity path in the diagram.
Therefore, sensors shall be applied at Point 2, and for advanced systems also at Point 1, to control the energy efficiency of the drying process and adapt it along the different phases of the process.

4 Course of Drying Process

A typical measurement of relative humidity RH_2, temperature T_2 and calculated dew point DP_2 along the full drying process in a tumble dryer is displayed in Figure 4. The data for Figure 4 has been taken from measurements in a state of the art tumble dryer.
Three phases can be observed, indicated with Phase I, II and III. Phase I is the heat up phase where the air is heated to a temperature set by the system. Phase II is the main drying phase where the relative humidity is on a constant level and Phase III is the finishing phase with decreasing relative humidity at constant temperature.
While Phase I doesn't need further discussion, Phase II is the full steam phase with wet laundry and lots of water available in the drum. This phase is critical to energy efficiency – where in an optimized program the relative humidity measured is high. The spikes in the humidity signal stem from spikes in temperature due to the steering cycle of the system. The response time of the sensor in this case is fast enough to sense the deviations in detail.
The finishing Phase III is characterized by the decreasing humidity and dew point temperature while temperature is even increasing. As the laundry ges dry the water available is not enough for saturating the air. Humidity and temperature information collected in Phase III serves as base for the definition of an individual cut-off criteria for the drying process.

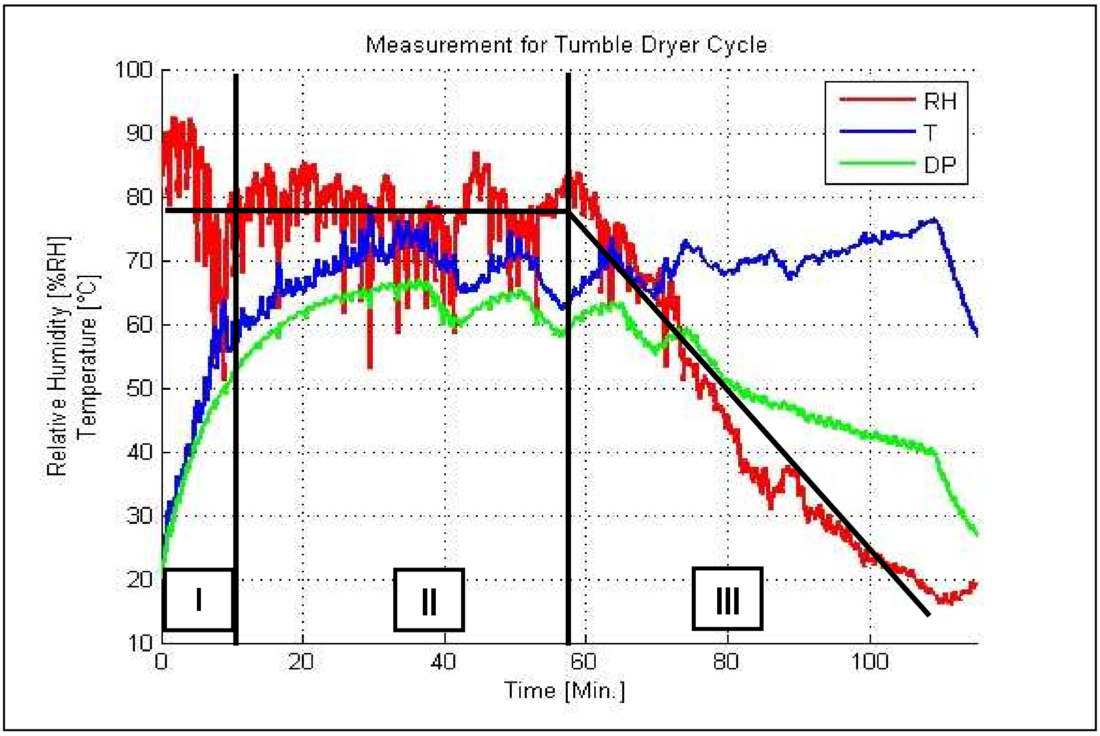

Figure 4: Measurement example of temperature (T_2) and relative humidity (RH_2) with calculated dew point (DP_2).

Ten measurements have been performed the same way, in the same drum with the same time controlled program running 1h and 35 minutes to examine the repeatability of the process. As start condition the same laundry - dry weight: 3 kg – has been washed and spin-dried the same way. After the washing and spin-drying cycle the weight of the wet laundry was 5.4 kg which corresponds to X = 80% residual moisture of the cloths, where residual moisture X is defined as follows:

$$X(\%) = \frac{Weight\ of\ water}{Weight\ of\ dry\ clothes}$$

After the drying process has been completed, the process was cut off at slightly different relative humidity values in Phase III of the process. Figure 5 shows the results of the different test runs: Relative humidity and the residual moisture X of the laundry depend very nicely on each other showing data points lined up on a line with very little scattering. The solid red line is a fitted line, indicating the correlation between relative humidity and residual moisture for this test set-up. These tests show that the drying state of the laundry can be well controlled by the proposed system, the system is very solid and the little scattering of the data gives evidence that a control of the residual moisture down to ±2% mass percent is possible.

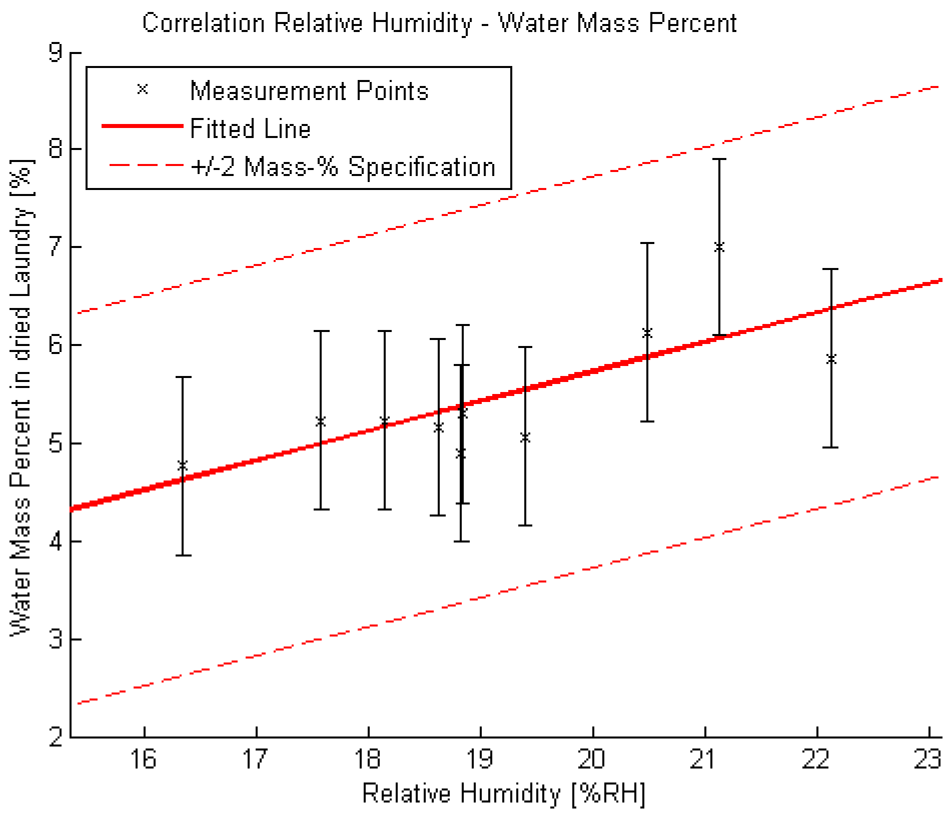

Figure 5: Correlation of relative humidity and weight of water in clothes

5 Sensor packaging, location and qualification

The integration of the sensor module is decisive for meaningful measurements and hence for an effective process control. Figure 6 displays a sketch of a packed sensor, mounted upside down in the flow channel after the drum as one possible realization of the sensor package. As the aerodynamic resistance should be minimal, the package must be round and small. There is a filter membrane on the package which should be water-proof (e.g. PTFE) which prevents contamination of the sensor but allows humidity to diffuse across to the sensor. Material choice of filter membrane should carefully be done in order to allow a good air exchange while no liquid water

should enter the inner volume above the sensor. In addition small particles should be hindered to enter into the sensor opening.
Another important issue is the sealing inside the package shown as red dots in the graphic. Glue or other means of sealing must be applied to divide the area around the sensor opening from the rest of the electronics and PCB. With this measure the volume below the filter membrane – where the sensor is located in – may be kept minimal and guarantees for fast response times of the sensor. Furthermore, it helps to prevent condensation in the module. Additionally, there is the problem of the thermal bridging from outside of the airflow channel (illustrated yellow). A correct temperature measurement of the humid air in the tubing by the sensor is decisive for the process control. Therefore thermal bridging must be avoided or kept as small as possible - it can be realised with good thermal isolation of the package.
The sensor applied should withstand high humidity environments. For this application SHT10 humidity and temperature sensor is recommended – it has passed several quality tests e.g. so called 85°C/85%RH test according to JESD22-A101-B. Also, the long term reliability of the overall module is important and depends strongly on the packaging of the sensor as the sensor element itself is robust against condensation, aging and high temperature and high humidity level conditions.

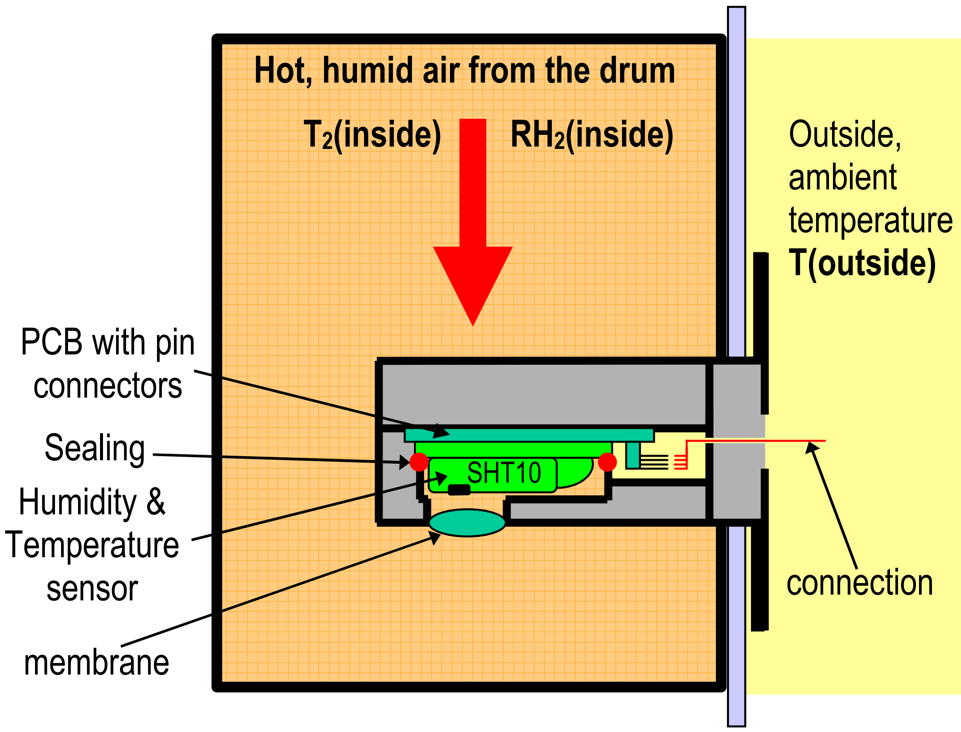

Figure6: Side view of an example of a sensor module: The sensor, in the grey package, is mounted upside down. The flow channel and the sensor package are not true to scale. Temperature inside the flow channel is different from outside temperature – hence thermal bridging should be kept minimal.

6 Summary

An innovative technology for drying process control is proposed, which supports energy saving and opens up new possibilities of drying program individualization. The cut-off criteria defined by this principle is independent of water quality, additives such as washing agents or fabric softeners and mixture of cloth materials, as the humidity measurement itself does not depend on this factors. Besides the advantage of combining a temperature & humidity sensor on the same chip, SHT10 satisfies all requirements for the appliance market such as long term stability and robust design. Integrators worldwide appreciate the ease of use, freedom of design-in possibilities, technical superiority and, not at last, the reasonable system costs.

7 Disclaimer

Revision History

Date	Revision	Changes
29.2.2008	1	First publication of document
11.12.2008	1.1	Confidentiality C1 and release on Internet