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Research Article

Design of an Arduino Based Low-Cost Air Conditioning Automation Device for Bovine Barns Using Temperature Humidity Index (THI)

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Abstract

Welfare and production efficiency of livestock, especially dairy cattle, in a barn are closely related with environmental factors such as temperature, humidity, etc. Therefore, the aim of this study is to design a low-cost automation device that is based on Temperature Humidity Index (THI). An Arduino microprocessor and associated sensors/electronics were used to design a prototype. The device collects, process and stores temperature, humidity and THI data in a minute interval for automation and long term management purposes. It is capable of estimating and storing theoretical daily reduction in milk production. Average actual daily milk production can also be entered to the system. The cost of the prototype was $ 238 that makes it affordable for low-income operations. Data was collected for a 6-month-period to test the performance of the prototype. Totally 1.4 megabyte of capacity is required for data storage. That makes the system affordable and easy to manage the data. The device was installed on a post in the middle of barn. It is found that below the lower limits of mild heat stress category (THI<83) total of 80 Simmental milking cows were not influenced from heat stress as confirmed by literature.

Keywords: Heat stress, temperature humidity index, Arduino, automation, environmental control

Sıcaklık Nem İndeksi (SNİ) Kullanılarak Büyükbaş Hayvan Barınakları İçin Arduino Tabanlı Düşük Maliyetli Bir Klima Otomasyon Cihazının Tasarımı

Öz

Çiftlik hayvanlarının, özellikle de süt sığırlarının bir ahırda refah ve üretim verimliliği, sıcaklık, nem gibi çevresel faktörlerle yakından ilişkilidir. Bu nedenle, çalışmanın amacı, sıcaklık nem indeksine (SNİ) dayanan düşük maliyetli bir otomasyon cihazı tasarlamaktır. Bir prototip tasarlamak için Arduino mikroişlemci ve uyumlu sensörler/elektronik malzemeler kullanıldı. Cihaz, otomasyon ve uzun vadeli yönetimsel amaçlar için dakikalık olarak sıcaklık, nem ve SNİ verilerini işleyebilmekte ve depoyabilmektedir. Cihaz, süt üretiminde teorik günlük azalmayı tahmin edebilir ve saklayabilir özelliklerdedir. Ortalama gerçek günlük süt üretimi de sisteme girilebilmektedir. Prototipin maliyeti 238$ olup düşük gelirli işletmeler için ekonomiktir. Veriler prototip performansını test etmek için 6 aylık bir süre boyunca toplanmıştır. Toplanan veriler için toplam 1.4 MB'lık küçük bir depolama kapasitesine gerek duyulmuştur. Bu ise, sistemin ekonomik ve verileri yönetimini kolay hale getirmiştir. Cihaz, ahırın ortasındaki bir direğe monte edilmiştir. Hafif ısı stresi kategorisinin (SNİ<83) alt sınırlarının altında 80 Simental süt sığırının literatürde doğrulandığı şekilde ısı stresinden çok fazla etkilenmediği tespit edilmiştir.

Anahtar Kelimeler: Arduino, çevre denetimi, ısı stresi, otomasyon, sıcaklık nem indeksi

Introduction

In most parts of the world, it is not possible to maintain the optimum environmental requirements of the domestic animals such as solar radiation, air movement and precipitation, especially temperature and relative humidity throughout the year (Bohmanova et al., 2007). Among these environmental conditions, high temperature and humidity that causes heat stress has important effects on behavior, production and hormonal activity of livestock. The relationship between temperature and humidity is directly influential in animal welfare and production profitability (Herbut and Angrecka, 2012), and even may cause death in young calves (Bray et al., 1994).

It is necessary to know the effects of environmental conditions on animal heat generation and losses to be able to plan a barn. Farm animals have a constant body temperature. If the animal does not cool down, the body temperature rises too much and heat stress occurs. Various indexes have been developed over the years to measure the heat stress resulting from the combination of above-mentioned environmental conditions. Since temperature and humidity are both controllable and easily measurable environmental factors, the most common of these indexes is the Temperature Humidity Index (THI) (Herbut and Angrecka, 2012). Although many formulas have been developed to calculate the THI, they are primarily based on the wet/dry bulb, dew-point temperature, and relative humidity.

If THI is calculated for outdoor conditions, temperature and relative humidity values generally obtained from meteorological stations, digital and manual thermometers and hygrometers. In literature there are different THI equations developed for cattle, goats, sheep and poultry (Collier et al., 2011; Menéndez-Buxadera et al., 2012; Bayhan et al., 2013; Zhang et al., 2017). Bohmanova et al. (2007) listed the most commonly used THI equations for dairy cattle. The following equation is one of the mostly used THI equations in literature (NRC, 1971). Also, it employs dry-bulb temperature and relative humidity which are directly read from temperature/relative humidity sensor.

$$\mathrm{THI} = (1.8 \times \mathrm{T}_{db} + 32) - (0.55 - 0.0055 \times \mathrm{RH}) \times (1.8 \times \mathrm{T}_{\mathrm{db}} - 26) \quad (1)$$

where; T_{db} is dry-bulb temperature (°C), and RH is relative humidity (%).

Table 1. Required management actions during heat stress based on the stress category

THI	Stress Category	Management action
THI < 72	No stress	-
72< THI < 80	Mild	Animal behavior and breathing is observed carefully. Cooling fans are operated and plenty of water supplied to the animals.
80 < THI < 90	Medium	If possible, evaporative cooling systems such as sprinkler and fan-pad cooling are activated. Barn is cooled via water flashing. Meanwhile animals are observed carefully.
THI > 90	Severe	Animals are moved as little as possible, for example, they are not sent to market. In addition to the measures in danger category, animals are not fed during the hottest hours of the day and the light level in the barn is reduced in order to reduce animal activity and thus heat production.

In different literature it is reported that cows are at risk of heat stress when THI exceeds 72 (Johnson, 1980; Du Preez et al., 1990; Armstrong, 1994; Ravagnolo et al., 2000). Some important signs of heat stress in dairy cattle are reduced feed intake, increased water intake, water loss via evaporation, body temperature, respiration rate, and changed metabolic rate (Armstrong, 1994). In order to control heat stress additional management is required. Management actions that can be considered based on the level of heat stress are given in Table 1 (Xin and Hamson, 1998).

Key and Sneeringer (2011) used THI as a tool to estimate global warming induced reduction in milk production in the United States. They reported that heat stress that will be increased due to global warming would cause milk losses between 5.1 and 6.8 % by 2090.

In another study, St-Pierre et al. (2003) used the THI equation that was reported in Ravagnolo et al. (2000) to estimate the reduction in milk production in the United States. They reported that heat stress causes loss of $ 897 million per year in the United State. In the same study, the relationship between THI and reduction in milk production was demonstrated by the following equation (Ravagnolo et al., 2000).

$$\mathrm{Milk_{loss}} = 0{,}0695 \times (\mathrm{THI_{max}} - \mathrm{THI}_{threshold})^2 \times \mathrm{D} \quad (2)$$

$$\mathrm{THI_{mean}} = \frac{\mathrm{THI_{max}} + \mathrm{THI_{min}}}{2} \quad (3)$$

where; $\mathrm{Milk_{loss}}$ is the reduction in milk production (kg cow^{-1} day^{-1}); $\mathrm{THI_{max}}$, $\mathrm{THI_{min}}$, and $\mathrm{THI_{mean}}$ are the maximum, minimum and mean THI observed during the day, respectively; $\mathrm{THI_{threshold}}$ is the threshold above which heat stress occurs for dairy cows; and D is the proportion of a day where $\mathrm{THI} > \mathrm{THI_{threshold}}$.

As outlined above it is possible to estimate heat stress and its effects on reduction in milk production using simple equations employing psychometrics parameters such as temperature and relative humidity.

In Turkey, most of the dairy operations owned by small family businesses and have a capacity of less than 50 milking cows (Uzundumlu, 2012). Almost all of these enterprises have inadequate environmental control systems. Natural ventilation systems are either ignored or insufficient. Similarly, there are almost no mechanical ventilation and cooling systems used in small scale family-owned enterprises. Adaptation of such technologies by the producers is highly difficult due to their low-incomes. Therefore, there is a need for cost-effective technology that can be used for environmental monitoring and control systems. The aim of this study is to design a device that employs the concept of THI. The system is designed to be able to control ventilation and/or cooling equipment, communicate with the producer(s) via cell phones when the heat stress conditions occur in the barn, monitor minute and daily THI changes, estimate daily reduction in milk production due to heat stress, and store temperature, relative humidity, THI, theoretical reduction in milk production due to heat stress and actual daily milk production rate in a database accessible via internet.

Material and Methods

Electronic design of the system

The main board of the system employs Arduino Uno R3 microcontroller. This card has a cheap and high capacity microprocessor that can easily integrate different sensors. The Arduino Uno R3 is a microcontroller board based on the ATmega328. It has 14 digital input/output pins, 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The SHT11 temperature/relative humidity sensor (SENSIRION, Laubisruetistrasse Staefa ZH, Switzerland) integrated on the microprocessor card is also a low-cost reliable technology. This sensor measures the temperature and relative humidity with high accuracies (±3 % and ±0.4 °C, respectively) and sends this value to the microcontroller unit. It can prevent noise and data loss problems due to the single way connection and the use of standard bandwidth signal.

The data is transferred to internet database via Arduino GSM Shield-Simcom/Sim800C (SIMCom Wireless Solutions Ltd., Shanghai, China). This shield sends temperature/relative humidity to the internet server via the mobile network. Its built-in antenna prevents interruption of data transmission in areas where the network signal is weak. This shield also provides a tool to remotely control air conditioning systems such as ventilation and/or cooling systems by using Short Message Service (SMS). In the design DS1307 Real-time Clock RTC Module (Gizmo Mechatronix Central Inc., Malate, Manila) is used to send the actual date and time information to the microcontroller, ensuring the timestamp of the data received from the sensor.

A 5-Inch Nextion HMI Touch TFT LCD Display (Nextion, Nanshan Dist., Shenzhen, GD, China) is used to display the instantaneous sensor data, on/off options of the air conditioning and other calculated outputs.

Only one sensor unit is installed since the test barn is small. The device records one reading per minute and data reading is not coordinated with milking which is done twice daily. The cost of Arduino based device is $ 238 including all above mentioned parts. The schematic representation of the device is given in Figure 1.

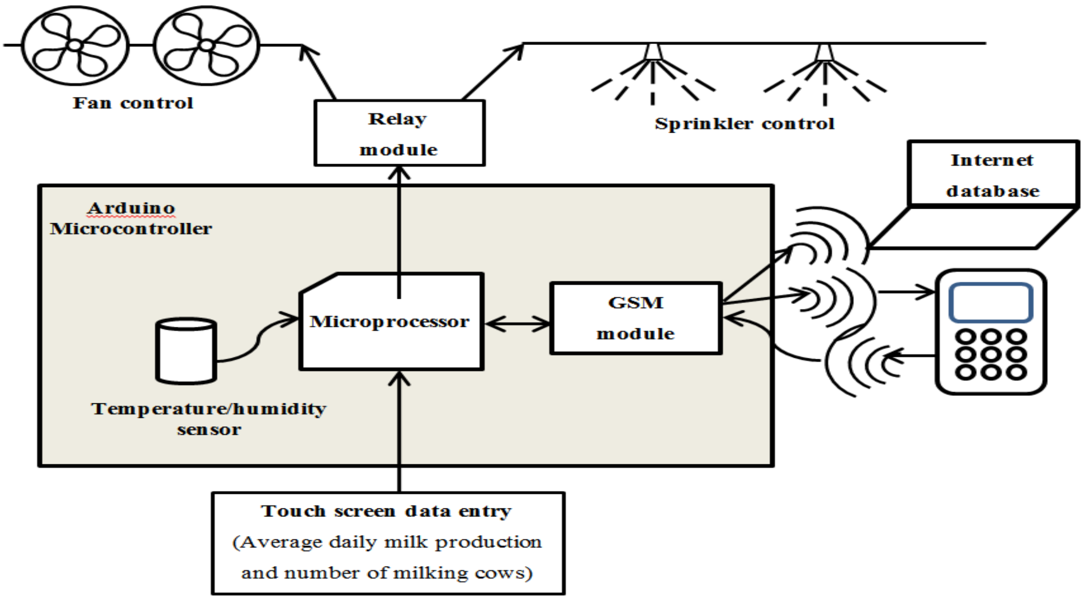

Figure 1. Schematic representation of the designed system

Software development

The platform that employs C/C ++ programming language provided by the microprocessor card is used for software development. The software has been developed for the remote control of fans and/or evaporative cooling system via a relay circuit according to the data received from the temperature/relative humidity sensor. In addition, measured temperature/ relative humidity and the calculated THI values are recorded by connecting to a remote database server over the Internet at the desired time intervals (1 minute in this study). In this way, data security is maintained and the database server is made accessible at anytime from anywhere. In the project, a relational database, MySQL, was used.

The software utilizes eq. (1) to calculate THI values for each minute. Daily milk production data is also entered into the system via LCD touch-screen. Thus, both stress categories and yields can be recorded during the research period. Also, at the end of each day the software calculates the estimated reduction in milk production using eq. (2). If there is any loss in milk production, this reduction is also sent to the database at 23:59 every day. According to the calculated THI values, the stress category was determined based on Table 1. As the sensor reads temperature and relative humidity values in every minute, the new THI value and recommended actions are displayed on the touch-screen for monitoring. A sample screenshot from the display of the device during operation is presented in Figure 2 followed by necessary explanations.

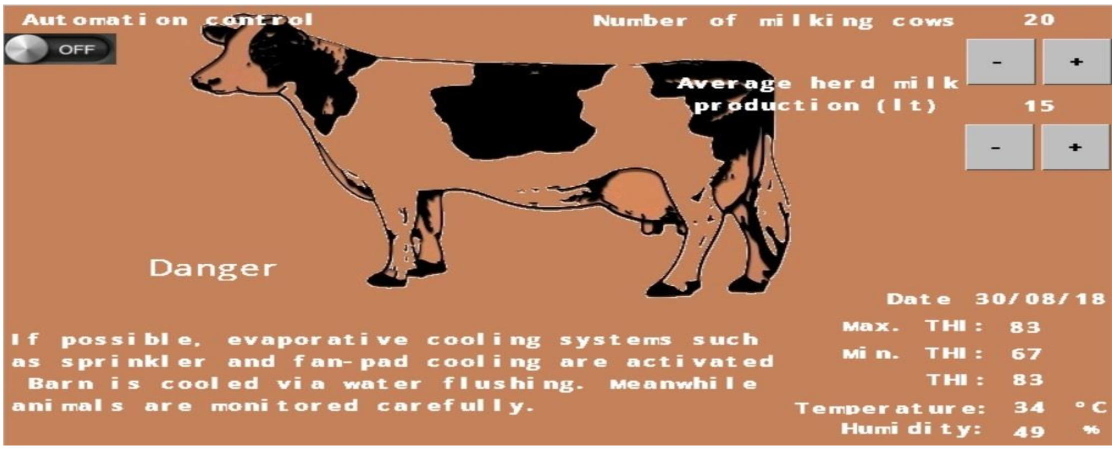

Figure 2. A sample screenshot from display

The numbers 1 to 4 refer to the following information, respectively;

1. The On/Off option is clicked on the touch screen to determine whether the system is connected to an air conditioning unit (fans/sprinklers, etc.). If the On status is selected, the device has the ability to operate air conditioning system when a stress category is reached. If the Off state is preferred, the device only displays the current data, the category of stress depending on this data and the actions that can be taken.

2. Which stress category is reached and what can be done in this category is written on the screen as a recommendation.

3. In this field, respectively, the date, the maximum and minimum THI values calculated up to that minute, and the THI value recorded in that minute are displayed. All values recorded in this field are sent to the database and can be accessed on the internet if desired.

Testing the system

A double-row loose dairy barn selected for testing the system is located in Çınarköprü Village, Biga District of Çanakkale Province, Turkey. It has a capacity of 80 Simmental milking dairy cows with an average milk production of 20 kg cow^{-1} day^{-1}. The barn is oriented along NE-SW directions and it is 30 m long and 15 m wide. Sidewalls are 2.8 m in height while the ridge height is 4.42 m. The barn has both mechanical and natural ventilation systems. Data was recorded between July 4, 2018 and January 3, 2019.

Data processing

The indoor data sent to the internet database by the device (temperature, relative

4. The number of cows milked on that day and the average milk yield obtained after milking are entered into this area. These data is also sent to database at the end of each day.

If the THI is greater than threshold value, 72, the producer is informed about the stress category by sending an SMS (alert, danger, emergency etc.). The device will send SMS every minute if a cooling system is not available in the barn. This will create a disturbing situation for the producer. Therefore, the frequency of sending SMS can be adjusted. However, the minutely data is still stored in the database.

The device can be connected to the air conditioning system and can provide automation of these systems. Also, when the message of any stress category has been reached in SMS, the user can control the relays of up to 4 air conditioning units by sending an SMS to the device.

humidity, THI, estimated reduction in daily milk production) was transferred to MS Excel format for further processing. Outdoor meteorological data was obtained from the Turkish State Meteorological Service for the study period (average hourly temperature, relative humidity, precipitation, wind speed/direction). Daily reduction in milk production in kg was calculated using eq. (2).

Results and Discussion

The main purpose of this study is to design a device that can be used to automate environmental conditioning systems. However, the device can also gather useful data for studies related to cow comfort and welfare. During the 6-month study period minute based data is collected. In animal welfare studies the quality and interval of data is highly critical. Ravagnolo et al. (2000) used daily mean temperature and humidity data obtained from weather stations. However, they pointed out that more accurate calculation of heat stress requires data collected shorter time intervals. That would make it possible to observe duration and strength of the stress period and use stress-management measures. From this point, our device provides a unique tool to collected indoor atmospheric data specific to heat stress studies. With the ports provided by Arduino microprocessor card it is also possible to connect the device to an external weather station to collect outdoor weather data as well.

The size of the data sent from the device to the database is 5.6 bpm. According to this, a total of 2.81 megabytes per year of data storage capacity is required. Hence, the size of data is quite small that makes it possible to collect longer terms for further studies.

In this section our purpose is not to evaluate the cow performance and productivity in comparison with THI. Therefore, the results will give an idea about the data collection and management capacity of the device. Yet, some data interpretation will be provided for the studied barn and period.

Mean daily indoor temperature, relative humidity and THI are plotted in Figure 3. During July, August and first 17 days of September even mean daily indoor temperature exceeded 25 °C which is considered to be upper limit of cow's comfort zone (Yousef, 1985; Hansen, 2013). For the same period lowest recorded temperature was 38 °C. The recorded mean daily THI values (82) also demonstrate that cows' were exposed to heat stress during the summer period. The threshold THI value is 72 for dairy cows in literature as detailed above. However, Gantner et al. (2017) reported that Simmental breed dairy cows are more tolerant to heat stress with a threshold value of 77 comparing to other breeds. Therefore, even though our device is programmed for threshold value of 72, for the remainder of the paper 77 will be considered.

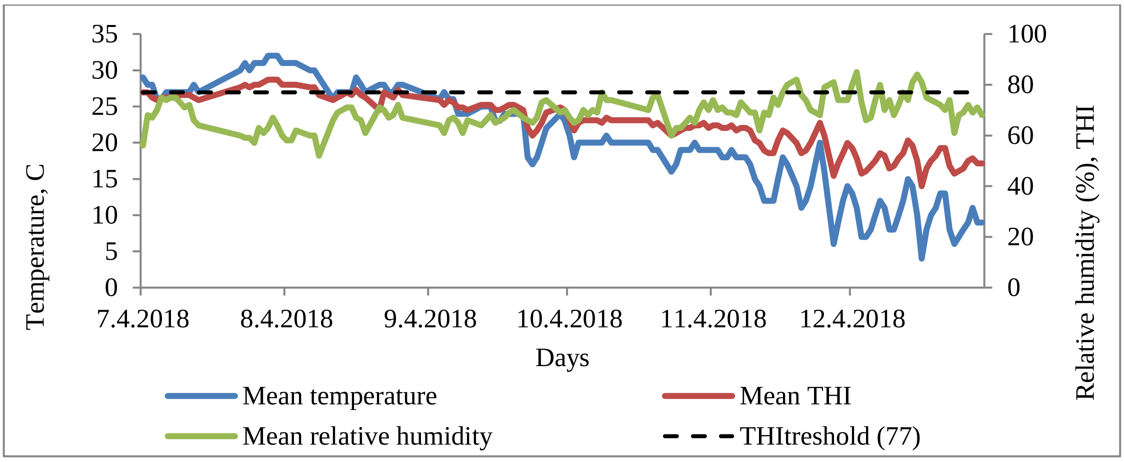

Figure 3. Mean daily ambient temperature, relative humidity and THI

Heat stress can be explained by combined effects of higher degrees of temperature and relative humidity which is remaining for longer time period. Our results showed that cows are exposed to maximum of 21-hour-heat stress during the hottest days of the study period. This is a useful data to evaluate the overall stress conditions observed during the study period.

Reduction in milk production in kg cow^{-1} day^{-1} is theoretically calculated using eq. (2). This equation takes the THI_{max} and $THI_{threshold}$ into account to calculate loss in milk production. Therefore, effects of other environmental factors such as feeding, noise, air quality etc. are omitted. Yet, our device not only can calculate THI-related yield reduction but also stores daily actual milk production rate for the herd. Mean yield loss for the days when heat stress occurred is calculated to be 1.4 kg cow^{-1} day^{-1}. Daily maximum THI and its effect on yield reduction is given in Figure 4. Also, on 8.4.2018, when the reduction in yield was at the maximum level, the temperature rose above 30 degrees. On the other hand, THI is above the threshold on the 9th of the month, but the yield reduction is not very high. As it will be discussed in details in the following of the manuscript this might be the higher levels of heat tolerance of Simmental breed. This data can be used to conduct further studies related to production economics.

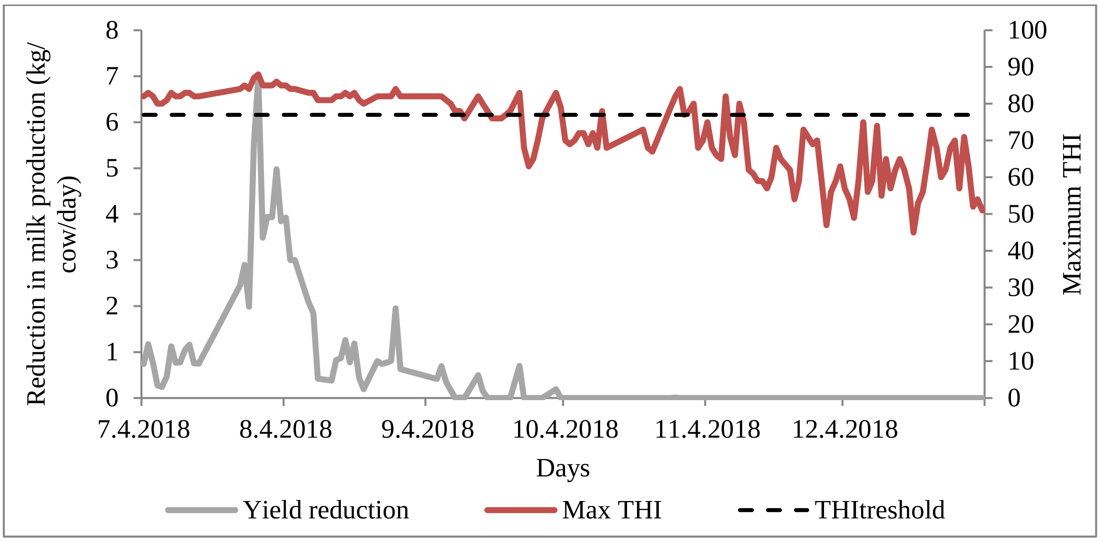

Figure 4. Daily reduction in milk production and THI

Daily average milk production per cow can be entered to the device as explained above. This allows user to evaluate the herd performance for stored criteria such as temperature, relative humidity, THI, reduction in milk yield. The mean indoor THI values and daily milk production rates are plotted together to see the effects of THI on production (Figure 5). Daily records indicate that maximum, minimum and average production rates are 27, 17, and 20.7 kg cow^{-1} day^{-1}, respectively. It is also seen that milk production yield is higher during the stress period which is theoretically incorrect. One explanation of this situation may be the feeding factor. From spring to early September, animals are fed on green grass. However, as the feeding of the animals with autumn is predominantly derived from dry grass, the yield begins to decrease.

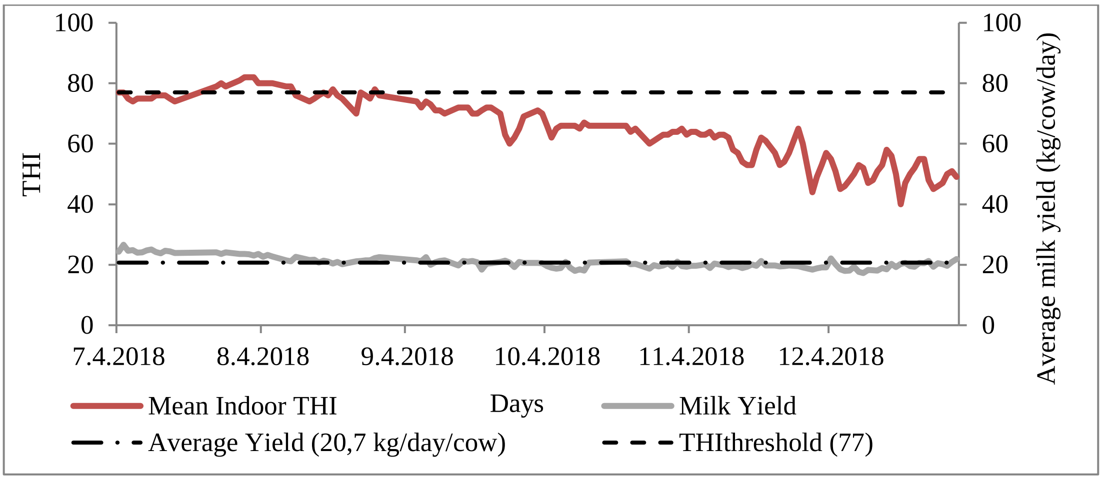

Figure 5. Relationship between mean THI and milk yield

Of those days heat stress recorded there were only about two weeks when THI exceeded 83. Also, Gantner et al. (2017) couldn't find a reduction in milk yield in older Simmental breeds for THI values ranging 66-80. Therefore, breed type might be another reason for this condition. Our experimental barn is equipped with evaporative cooling system. In another study, Toušová et al. (2017) found that higher temperatures caused an increase in individual cows' milk production. They concluded that use of evaporative cooling system might relieve heat stress and increase yield. Thus, our device with the capacity of automating environmental control systems such as evaporative cooling and mechanical might cause an increase in milk production during higher temperatures.

Conclusions

An Arduino-based low-cost automation device employing open source software was developed for low-income small dairy operations. The device not only automates the environmental control systems but also collects continuous minutely atmospheric data including temperature, relative humidity and THI. The system allows operators to enter daily average milk yield to the database. It also calculates theoretical daily reduction in average milk yield for management options. Its data storage requirement is about 2.81 megabytes per year. The cost of the device is $ 238 making it affordable for low-income small dairy operations.

The performance of the system was tested in a small dairy operation for 6 months. The good agreement between measured parameters and literature observed. The results of the study showed that a low-cost THI based automation and data collection device can be used in dairy operations. Long-term data collection capability makes the device suitable for scientific studies as well. Our future work will involve integrating other environmental sensors such as noise level detection, light intensity, etc into the prototype. Furthermore, feed and milk quality analysis will be conducted for better modeling purposes.

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