ON DIOPHANTINE EQUATIONS OF THE FORM $x^n + y^n = hp^m$

ALFRED BRAUER AND JAMES E. SHOCKLEY

E. Catalan [3] conjectured the following theorem: The square of a prime can be the sum of two cubes only if the prime $p = 3$. This conjecture was proved by L. Gegenbauer [4] as a special case of the following theorem:

Let $p$ be a prime and $n$ an integer which is not a power of 2. Then the Diophantine equation $x^n + y^n = p^m$ has no solution in relatively prime positive integers $x$ and $y$ unless $p = 3$, $m = 2$, $x = 2$, $y = 1$.

W. S. Baer [2] proved that for a given positive integer $h$ there exists at most a finite number of pairs of relatively prime positive integers $x$, $y$ where $(x^3 + y^3)/h$ is a power of a prime.

In this paper we will generalize these results by proving the following theorem:

**Theorem.** Let $n$ and $h$ be given positive integers where $n$ is not a power of 2. There exist at most a finite number of relatively prime positive integers $x$ and $y$, of primes $p$ and of integers $m$ such that

$$x^n + y^n = hp^m.$$  

The proof will give a method to find all possible solutions for given $n$ and $h$. The mentioned results of Gegenbauer and Baer follow as special cases.

For completeness we will prove the following well-known lemma.

**Lemma.** (See, for instance [1, p. 13].) Let $x$ and $y$ be relatively prime positive integers and $q$ an odd prime. We set $g(x, y) = (x^q + y^q)/(x+y)$ and denote the greatest common divisor of $g(x, y)$ and $(x+y)$ by $d$. Then

$$d = (x + y, g(x, y)) = 1 \text{ or } q.$$  

Moreover, in both cases $g(x, y) \not\equiv 0 \pmod{q^2}$.

**Proof.** We set $x+y=s$. Then

$$g(x, y) = \frac{(s - y)^q + y^q}{s}$$  

$$= s^{q-1} - \binom{q}{1} s^{q-2} y + \cdots + \binom{q}{q-1} y^{q-1}.$$

Received by the editors December 22, 1960.

951
Hence $d$ must divide $qy^{s-1}$ and since $(s, y) = 1$ we have that $d$ divides $q$. Thus (1) is proved. Moreover, if $s \equiv 0 \pmod{q}$ all terms of the right-hand side of (2) except the last one are divisible by $q^2$. If $s \not\equiv 0 \pmod{q}$, all terms except the first are divisible by $q$.

We now prove the theorem. It is sufficient to prove the theorem for the case that $n$ is an odd prime $q$ and $x > y$. Assume

$$x^s + y^s = hp^m. \tag{3}$$

For $m = 0$ the theorem is trivial. For $m = 1$ we obtain

$$x^s + y^s = x + y \cdot g(x, y) = hp. \tag{4}$$

Hence either $x + y$ or $g(x, y)$ is a divisor of $h$. Since

$$g(x, y) \geq x^{s-2}(x - y) + y^{s-1} \geq x^{s-2} + y^{s-1} \geq x + y \tag{5}$$

we have in either case that $x + y \leq h$ and we obtain at most a finite number of solutions.

For $m > 1$ we have to consider the finite number of factorizations of $h$ in the form $h = h_1h_2$. It follows from (3) that

$$x + y = h_1p^k, \quad 0 \leq k \leq m,$$

$$g(x, y) = h_2p^{m-k}. \tag{6}$$

The case $k = 0$ is trivial. If $k = m$, then by (4) $h_2 = g(x, y) \geq x + y$ so there are at most a finite number of $x$ and $y$ which satisfy (3). If $1 \leq k \leq m - 1$, then $(x + y, g(x, y)) = p$. Thus by the lemma $q = p$ and

$$x + y = h_1q^{m-1}, \tag{7}$$

$$g(x, y) = h_2q. \tag{8}$$

Thus by (4)

$$x + y \leq g(x, y) = h_2q,$$

and since $h$ and $q$ are given we obtain at most a finite number of solutions.

For the proof of the result of Gegenbauer we take $h = 1$. It is obvious that the cases $m = 0$ and $m = 1$ cannot occur. By (5), (6) and (7) we obtain $q^{m-1} \leq q$. Hence $m = 2$. Moreover, in (4) we only have equality if $q = 3$.

When finding all solutions of $x^s + y^s = hp^m$ we have only to consider those factorizations of $h$ for which $h_1$ contains only $q$ and primes of form $2qz + 1$. For suppose $t$ is a prime divisor of $h_1$. Then $g(x, y) \equiv 0 \pmod{t}$. Since $(x, y) = 1$ it follows that $(x, t) = (y, t) = 1$, so there is a positive integer $s$ such that $y^s \equiv sx \pmod{t}$. Hence
\[ g(x, y) = g(x, sx) = x^{s-1}g(s, 1) \equiv 0 \pmod{t}, \]

which implies that \( g(s, 1) \equiv 0 \pmod{t} \). Since \( q \) is a prime, \( g(x, 1) \) is the \( 2q \)th cyclotomic polynomial. It follows from the well-known theorem on cyclotomic polynomials that either \( t = q \) or \( t \) is of the form \( 2qz + 1 \).

**References**


**University of North Carolina**